Prince George's Community College

PGCC: PHYS 2040 - General Physics

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CHAPTER OVERVIEW

1: Waves and Vibrations

Topic hierarchy

1.1: Introduction

learning objectives

- Contrast mechanical and electromagnetic waves

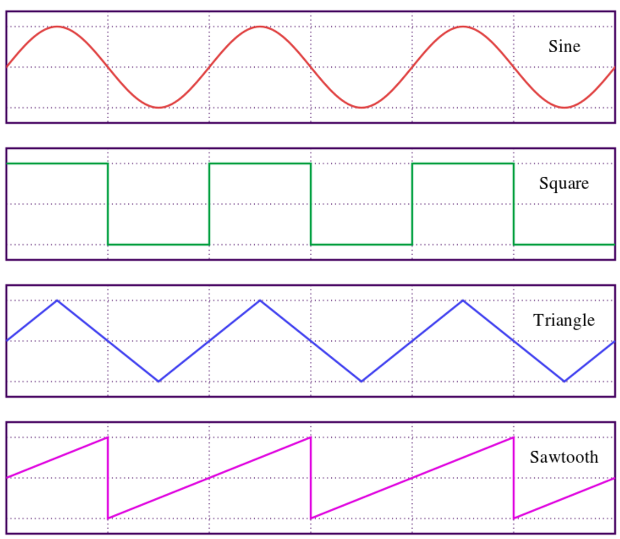
Overview

A wave is an oscillation that travels through space, accompanied by a transfer of energy. Wave motion transfers energy from one point to another, often with no permanent displacement of the particles of the medium —that is, with little or no associated mass transport. They consist, instead, of oscillations or vibrations around almost fixed locations. There are two main types of waves. Mechanical waves propagate through a medium, and the substance of this medium is deformed. The deformation reverses itself owing to restoring forces resulting from its deformation.

The second main type of wave, electromagnetic waves, do not require a medium (although they may still propagate through a medium). Instead, they consist of periodic oscillations in electrical and magnetic fields generated by charged particles, and can therefore travel through a vacuum.

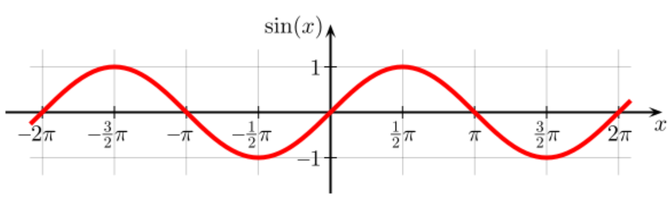
Wave Equation

The shape of a wave can take the form of any function that repeats itself over some characteristic spatial scale λλ, the wavelength (see). More generally, waveforms are scalar functions uu which satisfy the wave equation, $\frac{\partial^2 u}{\partial t^2} = c^2 \nabla^2 u$. This equation simply states that the acceleration of the waveform (Left: second derivative with respect to time) is proportional to the Laplacian (Right: second spatial derivative) of the same waveform. The constant of proportionality, c^2, is the square of the propagation speed of the wave.



Common waveforms: A sample of several common, simple waveforms. A waveform is a function that repeats in space.

Sine Wave



Plot of Sine: The sine function graphed on the Cartesian plane. In this graph, the angle *x* is given in radians (π = 180°).

Consider one of the most common waveforms, the sinusoid. A general form of a sinusoidal wave is $y(x,t) = A\sin(kx - \omega t + \phi)$, where A is the amplitude of the wave, ω is the wave's angular frequency, k is the wavenumber, and ϕ is the phase of the sine wave given in radians. This waveform gives the displacement position ("y") of a particle in a medium from its equilibrium as a function of both position "x" and time "t".

By taking derivatives, it is evident that the wave equation given above holds for $c = \frac{\omega}{k}$, which is also called the phase speed of the wave. To find the velocity of a particle in the medium at x and t, we take the temporal derivative of the waveform to get $\partial y(x,t) \partial t = -A\omega\cos(kx - \omega t + \phi)$. Likewise, to find the acceleration of the displaced particle in the medium at x and t, we take the second derivative to get $\frac{\partial^2 y(x,t)}{\partial t^2} = -A\omega^2\sin(kx - \omega t + \phi)$. Note the phase relationship among the trigonometric functions in $y(x,t), y'(x,t), y"(x,t)$. When the particle displacement is maximum or minimum, the velocity is 0. When the displacement is 0, particle velocity is either maximum or minimum. Similarly, the particle acceleration is maximum (or minimum) when the particle displacement is minimum (or maximum), respectively.

Arbitrary Wave

We looked closely into the sinusoidal wave. But how about waves that has a general form? One important aspect of the wave equation is its linearity: the wave equation is linear in *u* and it is left unaltered by translations in space and time. Since a wave with an arbitrary shape can be represented by a sum of many sinusoidal waves (this is called Fourier analysis), we can generate a great variety of solutions of the wave equation by translating and summing sine waves that we just looked closely into.

Key Points

- The wave equation requires that the second time derivative of the waveform be proportional to its second spatial derivative.
- Waveforms describe the shape of physical waves, and can take the form of any function that repeats in space.
- One of the most common waveforms in physics is the sinusoid. Since any arbitray waveform can be generated by adding a set of sine waves, the physics governing a wave of an arbitrary shape can be described by using its sine wave components.

Key Terms

- **waveform**: The shape of a physical wave, such as sound or electromagnetic radiation. The shape can be any function that repeats in space.
- **Fourier analysis**: The study of the way general functions may be represented or approximated by sums of simpler trigonometric functions.

1.2: Hooke's Law

learning objectives

- Generate the mathematical expression of Hooke's law

In mechanics (physics), Hooke's law is an approximation of the response of elastic (i.e., springlike) bodies. It states: the extension of a spring is in direct proportion with the load applied to it. For instance, the spring is pulled downwards with either no load, F_p, or twice F_p.

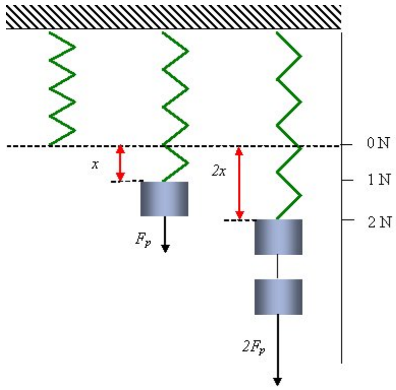
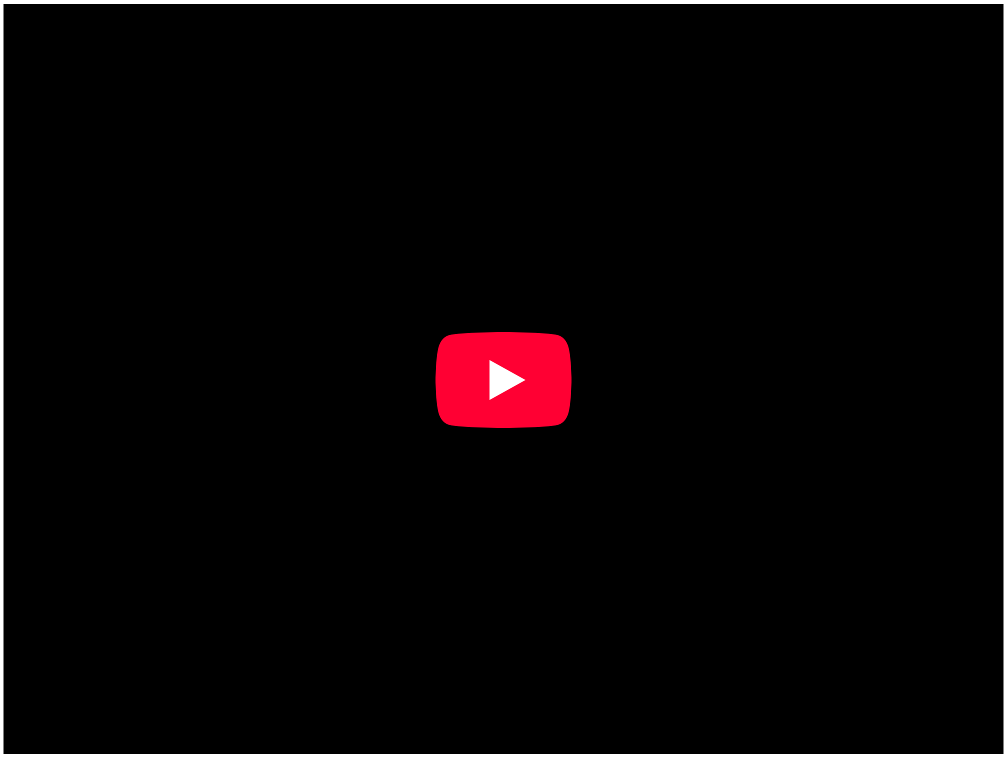
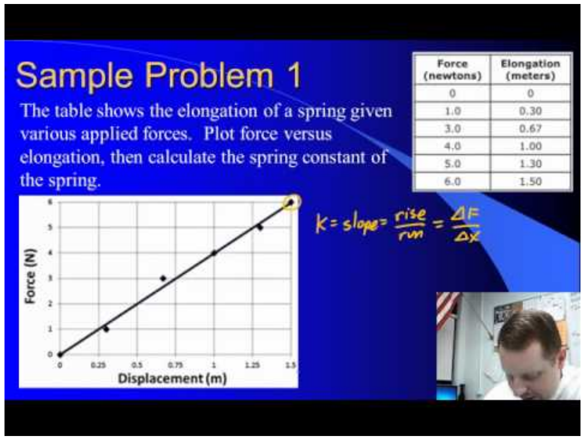


Diagram of Hooke's Law: The extension of the spring is linearly proportional to the force.





Springs and Hooke's Law: A brief overview of springs, Hooke's Law, and elastic potential energy for algebra-based physics students.

Many materials obey this law of elasticity as long as the load does not exceed the material's elastic limit. Materials for which Hooke's law is a useful approximation are known as linear-elastic or "Hookean" materials. Hookean materials are broadly defined and include springs as well as muscular layers of the heart. In simple terms, Hooke's law says that stress is directly proportional to strain. Mathematically, Hooke's law is stated as:

$$\mathrm{F}=-\mathrm{kx} \tag{1.2.1}$$

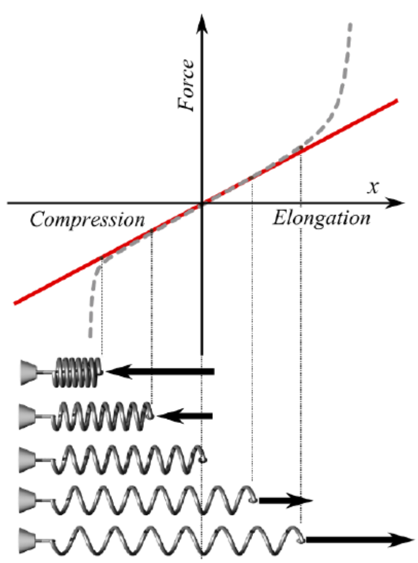
where:

- x is the displacement of the spring's end from its equilibrium position (a distance, in SI units: meters);
- F is the restoring force exerted by the spring on that end (in SI units: N or kg·m/s^2); and
- k is a constant called the rate or spring constant (in SI units: N/m or kg/s^2). When this holds, the behavior is said to be linear. If shown on a graph, the line should show a direct variation.

It's possible for multiple springs to act on the same point. In such a case, Hooke's law can still be applied. As with any other set of forces, the forces of many springs can be combined into one resultant force.

When Hooke's law holds, the behavior is linear; if shown on a graph, the line depicting force as a function of displacement should show a direct variation. There is a negative sign on the right hand side of the equation because the restoring force always acts in the opposite direction of the displacement (for example, when a spring is stretched to the left, it pulls back to the right).

Hooke's law is named after the 17th century British physicist Robert Hooke, and was first stated in 1660 as a Latin anagram, whose solution Hooke published in 1678 as *Ut tensio, sic vis*, meaning, "As the extension, so the force."



Hooke's Law: The red line in this graph illustrates how force, F, varies with position according to Hooke's law. The slope of this line corresponds to the spring constant k. The dotted line shows what the actual (experimental) plot of force might look like. The pictures of spring states at the bottom of the graph correspond to some points of the plot; the middle one is in the relaxed state (no force applied).

Elastic Potential Energy

If a force results in only deformation, with no thermal, sound, or kinetic energy, the work done is stored as elastic potential energy.

learning objectives

- Express elastic energy stored in a spring in a mathematical form

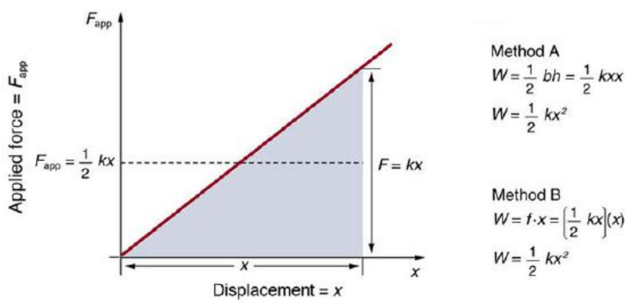
Elastic Potential Energy

In order to produce a deformation, work must be done. That is, a force must be exerted through a distance, whether you pluck a guitar string or compress a car spring. If the only result is deformation and no work goes into thermal, sound, or kinetic energy, then all the work is initially stored in the deformed object as some form of potential energy. Elastic energy is the potential mechanical energy stored in the configuration of a material or physical system when work is performed to distort its volume or shape. For example, the potential energy PE_{el} stored in a spring is

$$\mathrm{PE_{el}} = \frac{1}{2}\mathrm{kx}^2 \tag{1.2.2}$$

where k is the elastic constant and x is the displacement.

It is possible to calculate the work done in deforming a system in order to find the energy stored. This work is performed by an applied force F_{app}. The applied force is exactly opposite to the restoring force (action-reaction), and so $\mathrm{F_{app}} = \mathrm{kx}$. A graph shows the applied force versus deformation x for a system that can be described by Hooke's law. Work done on the system is force multiplied by distance, which equals the area under the curve, or $\frac{1}{2}\mathrm{kx}^2$ (Method A in the figure). Another way to determine the work is to note that the force increases linearly from 0 to kx, so that the average force is $\frac{1}{2}\mathrm{kx}$, the distance moved is x, and thus



Applied force versus deformation: A graph of applied force versus distance for the deformation of a system that can be described by Hooke's law is displayed. The work done on the system equals the area under the graph or the area of the triangle, which is half its base multiplied by its height, or $\mathrm{W} = \frac{1}{2}\mathrm{kx}^2$.

$\mathrm{W} = \mathrm{F_{app}}\mathrm{d} = (\frac{1}{2}\mathrm{kx})(\mathrm{x}) = \frac{1}{2}\mathrm{kx}^2$ (Method B in the figure).

Elastic energy of or within a substance is static energy of configuration. It corresponds to energy stored principally by changing the inter-atomic distances between nuclei. Thermal energy is the randomized distribution of kinetic energy within the material, resulting in statistical fluctuations of the material about the equilibrium configuration. There is some interaction, however. For example, for some solid objects, twisting, bending, and other distortions may generate thermal energy, causing the material's temperature to rise. This energy can also produce macroscopic vibrations sufficiently lacking in randomization to lead to oscillations that are merely the exchange between (elastic) potential energy within the object and the kinetic energy of motion of the object as a whole.

Key Points

- Mathematically, Hooke's Law can be written as $\mathrm{F} = -\mathrm{kx}$.
- Many materials obey this law as long as the load does not exceed the material's elastic limit.

- The rate or spring constant, k, relates the force to the extension in SI units: N/m or kg/s2.
- In order to produce a deformation, work must be done.
- The potential energy stored in a spring is given by $PE_{el} = \frac{1}{2}kx^2$, where k is the spring constant and x is the displacement.
- Deformation can also be converted into thermal energy or cause an object to begin oscillating.

Key Terms

- **elasticity**: The property by virtue of which a material deformed under the load can regain its original dimensions when unloaded
- **deformation**: A transformation; change of shape.
- **kinetic energy**: The energy possessed by an object because of its motion, equal to one half the mass of the body times the square of its velocity.
- **oscillating**: Moving in a repeated back-and-forth motion.

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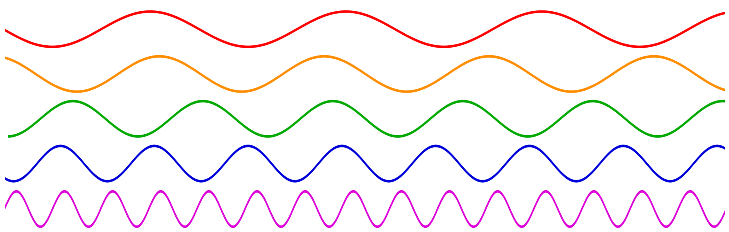
1.3: Periodic Motion

learning objectives

- Practice converting between frequency and period

Period and Frequency

The usual physics terminology for motion that repeats itself over and over is *periodic motion*, and the time required for one repetition is called the *period*, often expressed as the letter *T*. (The symbol *P* is not used because of the possible confusion with momentum.) One complete repetition of the motion is called a cycle. The frequency is defined as the number of cycles per unit time. Frequency is usually denoted by a Latin letter *f* or by a Greek letter *v* (nu). Note that period and frequency are reciprocals of each other.



Sinusoidal Waves of Varying Frequencies: Sinusoidal waves of various frequencies; the bottom waves have higher frequencies than those above. The horizontal axis represents time.

$$\mathrm{f}=\frac{1}{\mathrm{T}} \tag{1.3.1}$$

For example, if a newborn baby's heart beats at a frequency of 120 times a minute, its period (the interval between beats) is half a second. If you calibrate your intuition so that you expect *large frequencies* to be paired with *short periods*, and vice versa, you may avoid some embarrassing mistakes on physics exams.

Units

Locomotive Wheels: The locomotive's wheels spin at a frequency of f cycles per second, which can also be described as ω radians per second. The mechanical linkages allow the linear vibration of the steam engine's pistons, at frequency f, to drive the wheels.

In SI units, the unit of frequency is the *hertz* (Hz), named after the German physicist Heinrich Hertz: *1 Hz* indicates that an event repeats once per second. A traditional unit of measure used with rotating mechanical devices is revolutions per minute, abbreviated *RPM*. 60 RPM equals one hertz (i.e., one revolution per second, or a period of one second). The SI unit for period is the second.

Angular Frequency

Often periodic motion is best expressed in terms of angular frequency, represented by the Greek letter ω (omega). Angular frequency refers to the angular displacement per unit time (e.g., in rotation) or the rate of change of the phase of a sinusoidal waveform (e.g., in oscillations and waves), or as the rate of change of the argument of the sine function.

$$\mathrm{y}(\mathrm{t})=\sin(\theta(\mathrm{t}))=\sin(\omega\mathrm{t})=\sin(2\pi\mathrm{ft}) \tag{1.3.2}$$

$$\omega=2\pi\mathrm{f} \tag{1.3.3}$$

Angular frequency is often represented in units of radians per second (recall there are 2π radians in a circle).

Period of a Mass on a Spring

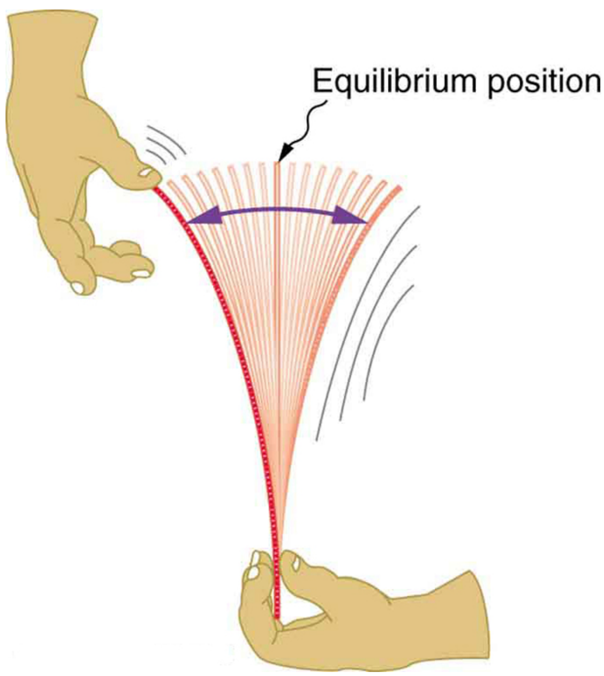
The period of a mass m on a spring of spring constant k can be calculated as $\mathrm{T}=2\pi\sqrt{\frac{\mathrm{m}}{\mathrm{k}}}$.

learning objectives

- Identify parameters necessary to calculate the period and frequency of an oscillating mass on the end of an ideal spring

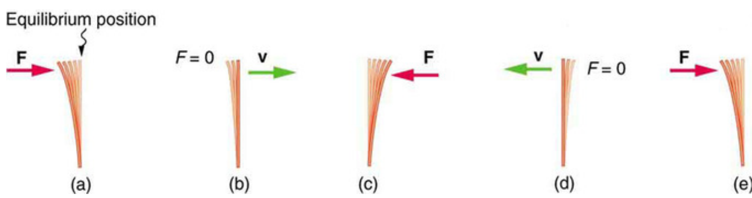
Understanding the Restoring Force

Newton's first law implies that an object oscillating back and forth is experiencing forces. Without force, the object would move in a straight line at a constant speed rather than oscillate. It is important to understand how the force on the object depends on the object's position. If an object is vibrating to the right and left, then it must have a leftward force on it when it is on the right side, and a rightward force when it is on the left side. In one dimension, we can represent the direction of the force using a positive or negative sign, and since the force changes from positive to negative there must be a point in the middle where the force is zero. This is the equilibrium point, where the object would stay at rest if it was released at rest. It is common convention to define the origin of our coordinate system so that *x* equals zero at equilibrium.



Oscillating Ruler: When displaced from its vertical equilibrium position, this plastic ruler oscillates back and forth because of the restoring force opposing displacement. When the ruler is on the left, there is a force to the right, and vice versa.

Consider, for example, plucking a plastic ruler shown in the first figure. The deformation of the ruler creates a force in the opposite direction, known as a *restoring force*. Once released, the restoring force causes the ruler to move back toward its stable equilibrium position, where the net force on it is zero. However, by the time the ruler gets there, it gains momentum and continues to move to the right, producing the opposite deformation. It is then forced to the left, back through equilibrium, and the process is repeated until dissipative forces (e.g., friction) dampen the motion. These forces remove mechanical energy from the system, gradually reducing the motion until the ruler comes to rest.



Restoring force, momentum, and equilibrium: (a) The plastic ruler has been released, and the restoring force is returning the ruler to its equilibrium position. (b) The net force is zero at the equilibrium position, but the ruler has momentum and continues to move to the right. (c) The restoring force is in the opposite direction. It stops the ruler and moves it back toward equilibrium again. (d) Now the ruler has momentum to the left. (e) In the absence of damping (caused by frictional forces), the ruler reaches its original position. From there, the motion will repeat itself.

Hooke's Law

The simplest oscillations occur when the restoring force is directly proportional to displacement. The name that was given to this relationship between force and displacement is Hooke's law:

$$F = kx \tag{1.3.4}$$

Here, F is the restoring force, x is the displacement from equilibrium or deformation, and k is a constant related to the difficulty in deforming the system (often called the spring constant or force constant). Remember that the minus sign indicates the restoring force is in the direction opposite to the displacement. The force constant k is related to the rigidity (or stiffness) of a system—the larger the force constant, the greater the restoring force, and the stiffer the system. The units of k are newtons per meter (N/m). For example, k is directly related to Young's modulus when we stretch a string. A typical physics laboratory exercise is to measure restoring forces created by springs, determine if they follow Hooke's law, and calculate their force constants if they do.

Mass on a Spring

A common example of an objecting oscillating back and forth according to a restoring force directly proportional to the displacement from equilibrium (i.e., following Hooke's Law) is the case of a mass on the end of an ideal spring, where "ideal" means that no messy real-world variables interfere with the imagined outcome.

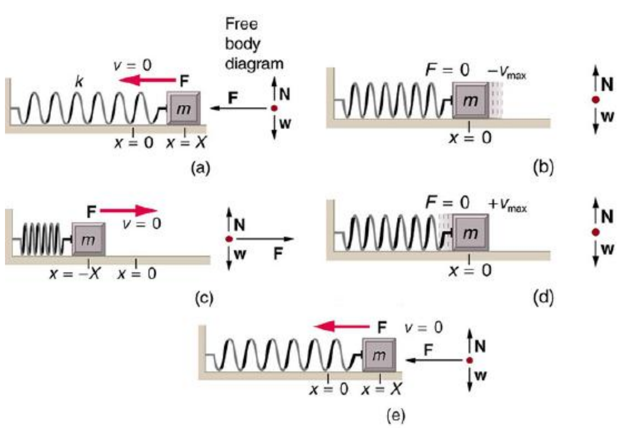
The motion of a mass on a spring can be described as Simple Harmonic Motion (SHM), the name given to oscillatory motion for a system where the net force can be described by Hooke's law. We can now determine how to calculate the period and frequency of an oscillating mass on the end of an ideal spring. The period T can be calculated knowing only the mass, m, and the force constant, k:

$$T = 2\pi\sqrt{\frac{m}{k}} \tag{1.3.5}$$

When dealing with $f = \frac{1}{T}$, the frequency is given by:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1.3.6}$$

We can understand the dependence of these equations on m and k intuitively. If one were to increase the mass on an oscillating spring system with a given k, the increased mass will provide more inertia, causing the acceleration due to the restoring force F to decrease (recall Newton's Second Law: $F = ma$). This will lengthen the oscillation period and decrease the frequency. In contrast, increasing the force constant k will increase the restoring force according to Hooke's Law, in turn causing the acceleration at each displacement point to also increase. This reduces the period and increases the frequency. The maximum displacement from equilibrium is known as the *amplitude X*.



Motion of a mass on an ideal spring: An object attached to a spring sliding on a frictionless surface is an uncomplicated simple harmonic oscillator. When displaced from equilibrium, the object performs simple harmonic motion that has an amplitude X and a period T. The object’s maximum speed occurs as it passes through equilibrium. The stiffer the spring is, the smaller the period T. The greater the mass of the object is, the greater the period T. (a) The mass has achieved its greatest displacement X to the right and now the restoring force to the left is at its maximum magnitude. (b) The restoring force has moved the mass back to its equilibrium point and is now equal to zero, but the leftward velocity is at its maximum. (c) The mass’s momentum has carried it to its maximum displacement to the right. The restoring force is now to the right, equal in magnitude and opposite in direction compared to (a). (d) The equilibrium point is reach again, this time with momentum to the right. (e) The cycle repeats.

Simple Harmonic Motion

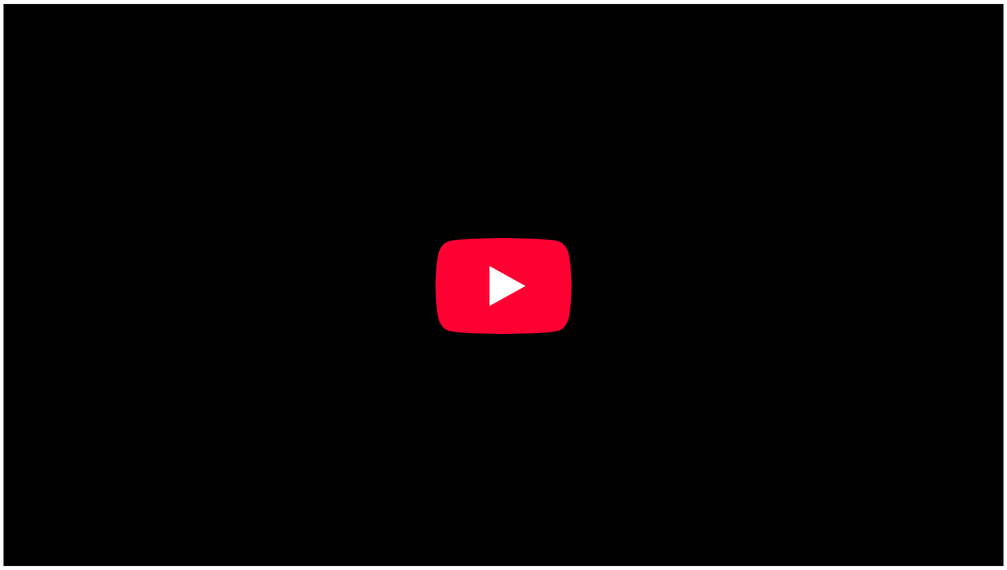
Simple harmonic motion is a type of periodic motion where the restoring force is directly proportional to the displacement.

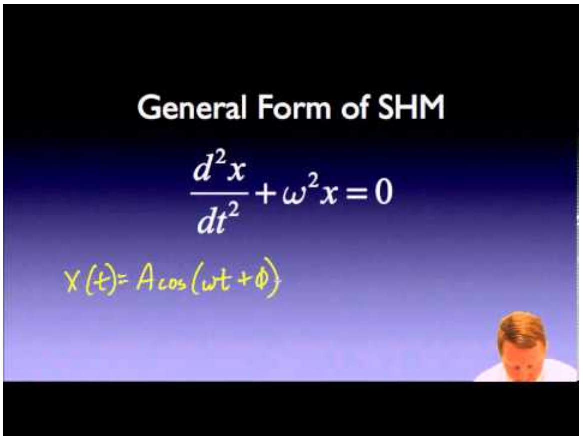
learning objectives

- Relate the restoring force and the displacement during the simple harmonic motion

Simple Harmonic Motion

Simple harmonic motion is a type of periodic motion where the restoring force is directly proportional to the displacement (i.e., it follows Hooke’s Law). It can serve as a mathematical model of a variety of motions, such as the oscillation of a spring. In addition, other phenomena can be approximated by simple harmonic motion, such as the motion of a simple pendulum, or molecular vibration.





Simple Harmonic Motion: A brief introduction to simple harmonic motion for calculus-based physics students.

Simple harmonic motion is typified by the motion of a mass on a spring when it is subject to the linear elastic restoring force given by Hooke’s Law. A system that follows simple harmonic motion is known as a *simple harmonic oscillator.*

Dynamics of Simple Harmonic Oscillation

For one-dimensional simple harmonic motion, the equation of motion (which is a second-order linear ordinary differential equation with constant coefficients) can be obtained by means of Newton's second law and Hooke's law.

$$F_{net} = m\frac{d^2x}{dt^2} = -kx, \tag{1.3.7}$$

where *m* is the mass of the oscillating body, *x* is its displacement from the equilibrium position, and *k* is the spring constant. Therefore:

$$\frac{d^2x}{dt^2} = -(\frac{k}{m})x. \tag{1.3.8}$$

Solving the differential equation above, a solution which is a sinusoidal function is obtained.

$$x(t) = c_1\cos(\omega t) + c_2\sin(\omega t) = A\cos(\omega t - \varphi), \tag{1.3.9}$$

where

$$\omega = \sqrt{\frac{k}{m}}, \tag{1.3.10}$$

$$A = \sqrt{c_1^2 + c_2^2}, \tag{1.3.11}$$

$$\tan\varphi = (\frac{c_2}{c_1}). \tag{1.3.12}$$

In the solution, c_1 and c_2 are two constants determined by the initial conditions, and the origin is set to be the equilibrium position. Each of these constants carries a physical meaning of the motion: A is the amplitude (maximum displacement from the equilibrium position), $\omega = 2\pi f$ is the angular frequency, and φ is the phase.

We can use differential calculus and find the velocity and acceleration as a function of time:

$$v(t) = \frac{dx}{dt} = -A\omega\sin(\omega t - \varphi) \tag{1.3.13}$$

$$a(t) = \frac{d^2x}{dt^2} = -A\omega^2\cos(\omega t - \varphi). \tag{1.3.14}$$

Acceleration can also be expressed as a function of displacement:

$$a(t) = -\omega^2 x. \tag{1.3.15}$$

Then since $\omega = 2\pi f$,

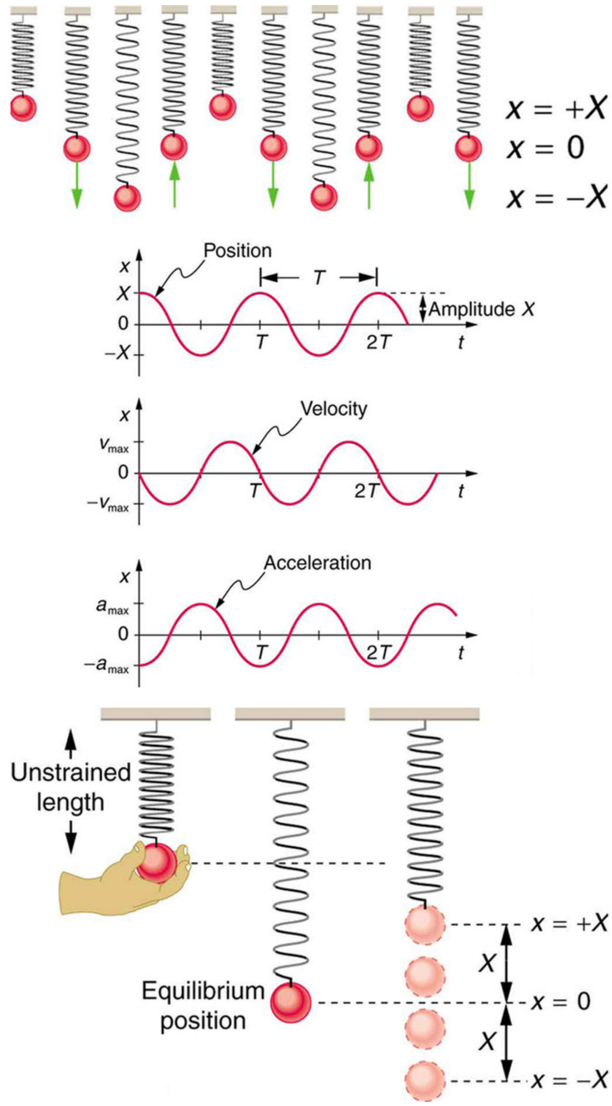
$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}. \tag{1.3.16}$$

Recalling that $T = \frac{1}{f}$,

$$T = 2\pi\sqrt{\frac{m}{k}}. \tag{1.3.17}$$

Using Newton's Second Law, Hooke's Law, and some differential Calculus, we were able to derive the period and frequency of the mass oscillating on a spring that we encountered in the last section! Note that the period and frequency are completely independent of the amplitude.

The below figure shows the simple harmonic motion of an object on a spring and presents graphs of x(t),v(t), and a(t) versus time. You should learn to create mental connections between the above equations, the different positions of the object on a spring in the cartoon, and the associated positions in the graphs of x(t), v(t), and a(t).



Visualizing Simple Harmonic Motion: Graphs of x(t),v(t), and a(t) versus t for the motion of an object on a spring. The net force on the object can be described by Hooke's law, and so the object undergoes simple harmonic motion. Note that the initial position has the vertical displacement at its maximum value X; v is initially zero and then negative as the object moves down; and the initial acceleration is negative, back toward the equilibrium position and becoming zero at that point.

Simple Harmonic Motion and Uniform Circular Motion

Simple harmonic motion is produced by the projection of uniform circular motion onto one of the axes in the x-y plane.

learning objectives

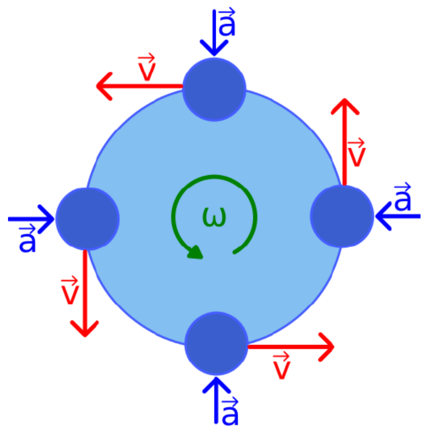
- Describe relationship between the simple harmonic motion and uniform circular motion

Uniform Circular Motion

Uniform circular motion describes the motion of a body traversing a circular path at constant speed. The distance of the body from the center of the circle remains constant at all times. Though the body's speed is constant, its velocity is not constant: velocity (a vector quantity) depends on both the body's speed and its direction of travel. Since the body is constantly changing direction as it travels around the circle, the velocity is changing also. This varying velocity indicates the presence of an acceleration called the centripetal acceleration. Centripetal acceleration is of constant magnitude and directed at all times towards the center of the circle. This acceleration is, in turn, produced by a centripetal force —a force in constant magnitude, and directed towards the center.

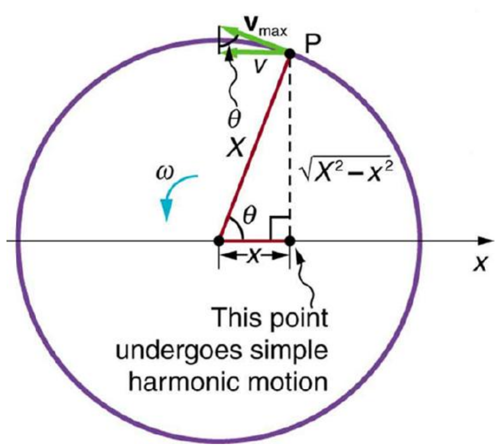
Velocity

The above figure illustrates velocity and acceleration vectors for uniform motion at four different points in the orbit. Since velocity *v* is tangent to the circular path, no two velocities point in the same direction. Although the object has a constant speed, its direction is always changing. This change in velocity is due to an acceleration, *a*, whose magnitude is (like that of the velocity) held constant, but whose direction also is always changing. The acceleration points radially inwards (centripetally) and is perpendicular to the velocity. This acceleration is known as centripetal acceleration.



Uniform Circular Motion (at Four Different Point in the Orbit): Velocity v and acceleration a in uniform circular motion at angular rate ω; the speed is constant, but the velocity is always tangent to the orbit; the acceleration has constant magnitude, but always points toward the center of rotation

Displacement around a circular path is often given in terms of an angle θ. This angle is the angle between a straight line drawn from the center of the circle to the objects starting position on the edge and a straight line drawn from the objects ending position on the edge to center of the circle. See for a visual representation of the angle where the point p started on the x- axis and moved to its present position. The angle θ describes how far it moved.



Projection of Uniform Circular Motion: A point P moving on a circular path with a constant angular velocity ω is undergoing uniform circular motion. Its projection on the x-axis undergoes simple harmonic motion. Also shown is the velocity of this point around the circle, v−max, and its projection, which is v. Note that these velocities form a similar triangle to the displacement triangle.

For a path around a circle of radius *r*, when an angle θ(measured in radians) is swept out, the distance traveled on the edge of the circle is $s = r\theta$. You can prove this yourself by remembering that the circumference of a circle is 2πr, so if the object traveled around the whole circle (one circumference) it will have gone through an angle of 2π radians and traveled a distance of 2πr. Therefore, the speed of travel around the orbit is:

$$v = r\frac{d\theta}{dt} = r\omega, \tag{1.3.18}$$

where the angular rate of rotation is ω. (Note that $\omega = \frac{v}{r}$.) Thus,v is a constant, and the velocity vector v also rotates with constant magnitude v, at the same angular rate ω.

Acceleration

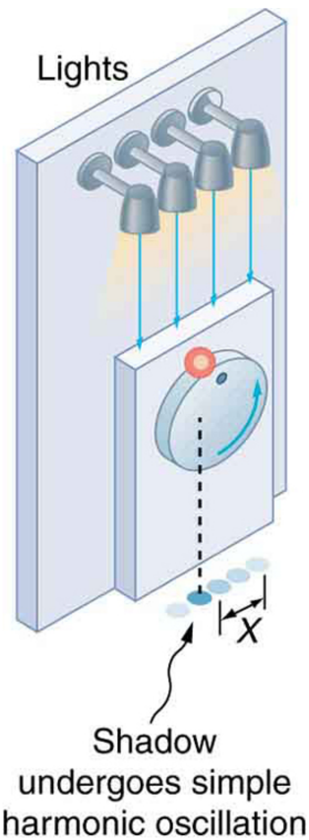
The acceleration in uniform circular motion is always directed inward and is given by:

$$a = v\frac{d\theta}{dt} = v\omega = \frac{v^2}{r}. \tag{1.3.19}$$

This acceleration acts to change the direction of v, but not the speed.

Simple Harmonic Motion from Uniform Circular Motion

There is an easy way to produce simple harmonic motion by using uniform circular motion. The figure below demonstrates one way of using this method. A ball is attached to a uniformly rotating vertical turntable, and its shadow is projected onto the floor as shown. The shadow undergoes simple harmonic motion.



Shadow of a Ball Undergoing Simple Harmonic Motion: The shadow of a ball rotating at constant angular velocity ω on a turntable goes back and forth in precise simple harmonic motion.

The next figure shows the basic relationship between uniform circular motion and simple harmonic motion. The point P travels around the circle at constant angular velocity ω. The point P is analogous to the ball on a turntable in the figure above. The projection of the position of P onto a fixed axis undergoes simple harmonic motion and is analogous to the shadow of the object. At a point in time assumed in the figure, the projection has position x and moves to the left with velocity v. The velocity of the point P around the circle equals $|v_{max}|$. The projection of $|v_{max}|$ on the x-axis is the velocity v of the simple harmonic motion along the x-axis.

To see that the projection undergoes simple harmonic motion, note that its position x is given by:

$$x = X\cos\theta, \tag{1.3.20}$$

where $\theta = \omega t$, ω is the constant angular velocity, and X is the radius of the circular path. Thus,

$$x = X \cos \omega t. \tag{1.3.21}$$

The angular velocity ω is in radians per unit time; in this case 2π radians is the time for one revolution T. That is, $\omega = \frac{2\pi}{T}$. Substituting this expression for ω, we see that the position x is given by:

$$x(t) = \cos(\frac{2\pi t}{T}) = \cos(2\pi f t). \tag{1.3.22}$$

Note: This equation should look familiar from our earlier discussion of simple harmonic motion.

The Simple Pendulum

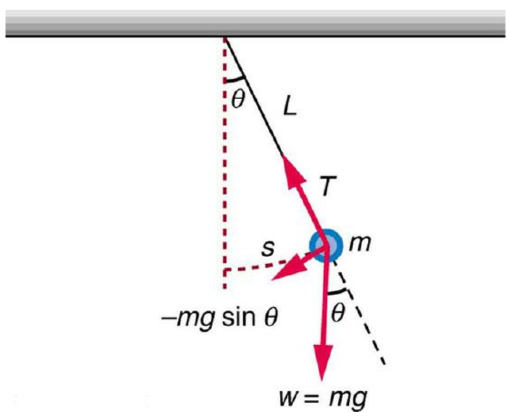
A simple pendulum acts like a harmonic oscillator with a period dependent only on L and g for sufficiently small amplitudes.

learning objectives

- Identify parameters that affect the period of a simple pendulum

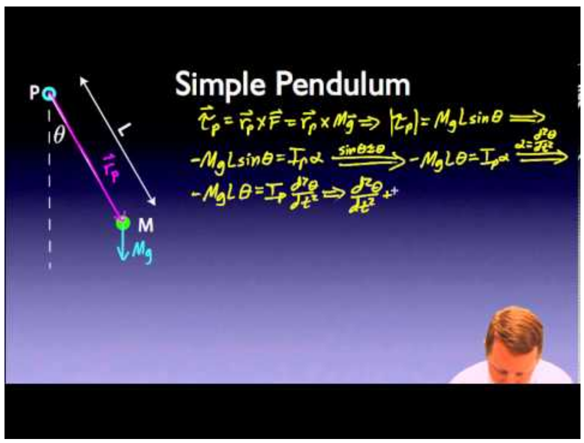
The Simple Pendulum

A pendulum is a weight suspended from a pivot so that it can swing freely. When a pendulum is displaced sideways from its resting equilibrium position, it is subject to a restoring force; after it reaches its highest point in its swing, gravity will accelerate it back toward the equilibrium position. When released, the restoring force combined with the pendulum's mass causes it to oscillate about the equilibrium position, swinging back and forth.



Simple Pendulum: A simple pendulum has a small-diameter bob and a string that has a very small mass but is strong enough not to stretch appreciably. The linear displacement from equilibrium is s, the length of the arc. Also shown are the forces on the bob, which result in a net force of −mgsinθ toward the equilibrium position—that is, a restoring force.

For small displacements, a pendulum is a simple harmonic oscillator. A simple pendulum is defined to have an object that has a small mass, also known as the pendulum bob, which is suspended from a wire or string of negligible mass, such as shown in the illustrating figure. Exploring the simple pendulum a bit further, we can discover the conditions under which it performs simple harmonic motion, and we can derive an interesting expression for its period.



Pendulums: A brief introduction to pendulums (both ideal and physical) for calculus-based physics students from the standpoint of simple harmonic motion.

We begin by defining the displacement to be the arc length *s*. We see from the figure that the net force on the bob is tangent to the arc and equals $-mg\sin\theta$. (The weight *mg* has components $mg\cos\theta$ along the string and $mg\sin\theta$ tangent to the arc.) Tension in the string exactly cancels the component $mg\cos\theta$ parallel to the string. This leaves a net restoring force drawing the pendulum back toward the equilibrium position at $\theta = 0$.

Now, if we can show that the restoring force is directly proportional to the displacement, then we have a simple harmonic oscillator. In trying to determine if we have a simple harmonic oscillator, we should note that for small angles (less than about 15º), $\sin\theta\approx\theta$ ($\sin\theta$ and θ differ by about 1% or less at smaller angles). Thus, for angles less than about 15º, the restoring force F is

$$\mathrm{F} \approx -\mathrm{mg}\theta. \tag{1.3.23}$$

The displacement s is directly proportional to θ. When θ is expressed in radians, the arc length in a circle is related to its radius (*L* in this instance) by:

s=Lθs=Lθ

so that

$$\theta = \mathrm{sL}. \tag{1.3.24}$$

For small angles, then, the expression for the restoring force is:

$$\mathrm{F} \approx \frac{\mathrm{mgL}}{\mathrm{s}}. \tag{1.3.25}$$

This expression is of the form of Hooke's Law:

$$F \approx -kx \tag{1.3.26}$$

where the force constant is given by $k=mg/L$ and the displacement is given by $x=s$. For angles less than about 15º, the restoring force is directly proportional to the displacement, and the simple pendulum is a simple harmonic oscillator.

Using this equation, we can find the period of a pendulum for amplitudes less than about 15º. For the simple pendulum:

$$T = 2\pi\sqrt{\frac{m}{k}} = 2\pi\sqrt{\frac{m}{\frac{mg}{L}}}. \tag{1.3.27}$$

Thus,

$$T = 2\pi\sqrt{\frac{L}{g}} \tag{1.3.28}$$

or the period of a simple pendulum. This result is interesting because of its simplicity. The only things that affect the period of a simple pendulum are its length and the acceleration due to gravity. The period is completely independent of other factors, such as mass. Even simple pendulum clocks can be finely adjusted and accurate. Note the dependence of T on g. If the length of a pendulum is precisely known, it can actually be used to measure the acceleration due to gravity. If θ is less than about 15º, the period T for a pendulum is nearly independent of amplitude, as with simple harmonic oscillators. In this case, the motion of a pendulum as a function of time can be modeled as:

$$\theta(t) = \theta_o \cos(\frac{2\pi t}{T}) \tag{1.3.29}$$

For amplitudes larger than 15º, the period increases gradually with amplitude so it is longer than given by the simple equation for T above. For example, at an amplitude of θ_0 = 23° it is 1% larger. The period increases asymptotically (to infinity) as $\theta_0$approaches 180°, because the value θ_0 = 180° is an unstable equilibrium point for the pendulum.

The Physical Pendulum

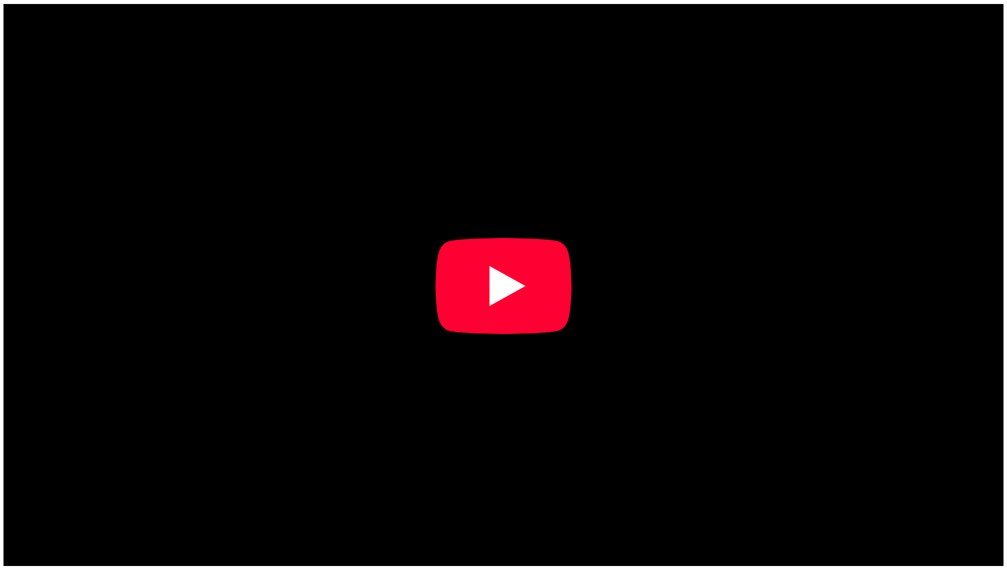
The period of a physical pendulum depends upon its moment of inertia about its pivot point and the distance from its center of mass.

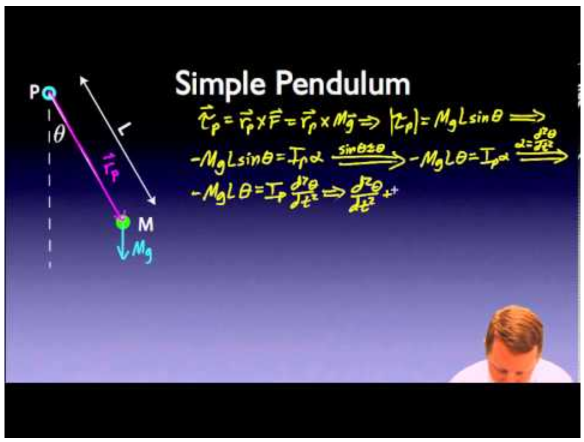
learning objectives

- Identify parameters that affect the period of a physical pendulum

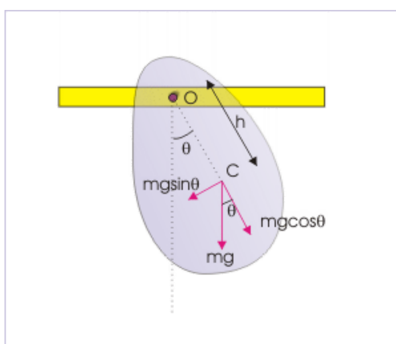
The Physical Pendulum

Recall that a simple pendulum consists of a mass suspended from a massless string or rod on a frictionless pivot. In that case, we are able to neglect any effect from the string or rod itself. In contrast, a *physical pendulum* (sometimes called a compound pendulum) may be suspended by a rod that is not massless or, more generally, may be an arbitrarily-shaped, rigid body swinging by a pivot (see). In this case, the pendulum's period depends on its moment of inertia around the pivot point.





Pendulums – Physical Pendulum: A brief introduction to pendulums (both ideal and physical) for calculus-based physics students from the standpoint of simple harmonic motion.



A Physical Pendulum: An example showing how forces act through center of mass. We can calculate the period of this pendulum by determining the moment of inertia of the object around the pivot point.

Gravity acts through the center of mass of the rigid body. Hence, the length of the pendulum used in equations is equal to the linear distance between the pivot and the center of mass (h).

The equation of torque gives:

$$\tau = \mathrm{I}\alpha, \tag{1.3.30}$$

where α is the angular acceleration, τ is the torque, and I is the moment of inertia.

The torque is generated by gravity so:

$$\tau = \mathrm{mgh} \sin\theta, \tag{1.3.31}$$

where h is the distance from the center of mass to the pivot point and θ is the angle from the vertical.

Hence, under the small-angle approximation sin\theta \approx \theta,

$$\alpha \approx -\frac{\mathrm{mgh}\theta}{\mathrm{I}}. \tag{1.3.32}$$

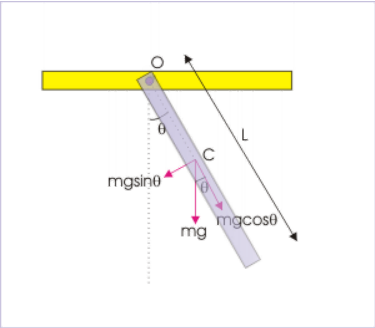
This is of the same form as the conventional simple pendulum and this gives a period of:

$$\mathrm{T} = 2\pi\sqrt{\frac{\mathrm{I}}{\mathrm{mgh}}}. \tag{1.3.33}$$

And a frequency of:

\[\mathrm{f=\dfrac{1}{T}=\dfrac{1}{2π}\sqrt{\dfrac{mgh}{I}}.}\]

In case we know the moment of inertia of the rigid body, we can evaluate the above expression of the period for the physical pendulum. For illustration, let us consider a uniform rigid rod, pivoted from a frame as shown (see). Clearly, the center of mass is at a distance *L/2* from the point of suspension:



Uniform Rigid Rod: A rigid rod with uniform mass distribution hangs from a pivot point. This is another example of a physical pendulum.

$$\mathrm{h} = \frac{\mathrm{L}}{2}. \tag{1.3.34}$$

The moment of inertia of the rigid rod about its center is:

$$\mathrm{I_c} = \frac{\mathrm{mL^2}}{12}. \tag{1.3.35}$$

However, we need to evaluate the moment of inertia about the pivot point, not the center of mass, so we apply the parallel axis theorem:

$$\mathrm{I_o} = \mathrm{I_c} + \mathrm{mh^2} = \frac{\mathrm{mL^2}}{12} + \mathrm{m}\left(\frac{\mathrm{L}}{2}\right)^2 = \frac{\mathrm{mL^2}}{3}. \tag{1.3.36}$$

Plugging this result into the equation for period, we have:

$$\mathrm{T} = 2\pi\sqrt{\frac{\mathrm{I}}{\mathrm{mgh}}} = 2\pi\sqrt{\frac{\mathrm{2mL^2}}{\mathrm{3mgL}}} = 2\pi\sqrt{\frac{\mathrm{2L}}{\mathrm{3g}}}. \tag{1.3.37}$$

The important thing to note about this relation is that the period is still independent of the mass of the rigid body. However, it is not independent of the *mass distribution* of the rigid body. A change in shape, size, or mass distribution will change the moment of inertia. This, in turn, will change the period.

As with a simple pendulum, a physical pendulum can be used to measure *g*.

Energy in a Simple Harmonic Oscillator

The total energy in a simple harmonic oscillator is the constant sum of the potential and kinetic energies.

learning objectives

- Explain why the total energy of the harmonic oscillator is constant

Energy in a Simple Harmonic Oscillator

To study the energy of a simple harmonic oscillator, we first consider all the forms of energy it can have. Recall that the potential energy (*PE)*, stored in a spring that follows Hooke's Law is:

$$\mathrm{PE}=\frac{1}{2}\mathrm{kx}^2, \tag{1.3.38}$$

where PE is the potential energy, *k* is the spring constant, and *x* is the magnitude of the displacement or deformation. Because a simple harmonic oscillator has no *dissipative forces* , the other important form of energy is kinetic energy (*KE)*. Conservation of energy for these two forms is:

$$\mathrm{KE}+\mathrm{PE}=\mathrm{constant}, \tag{1.3.39}$$

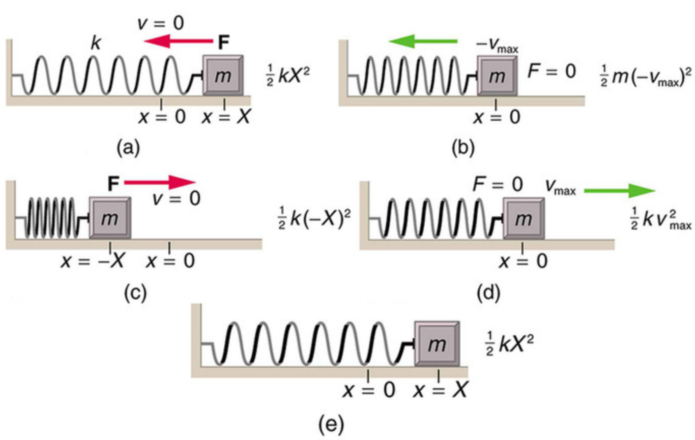
which can be written as:

$$\frac{1}{2}\mathrm{mv}^2+\frac{1}{2}\mathrm{kx}^2=\mathrm{constant}. \tag{1.3.40}$$

This statement of conservation of energy is valid for *all* simple harmonic oscillators, including ones where the gravitational force plays a role. For example, for a simple pendulum we replace the velocity with $v=L\omega$, the spring constant with $k=mg/L$, and the displacement term with $x=L\theta$. Thus:

$$\frac{1}{2}\mathrm{mL}^2\omega^2+\frac{1}{2}\mathrm{mgL}\theta^2=\mathrm{constant}. \tag{1.3.41}$$

In the case of undamped, simple harmonic motion, the energy oscillates back and forth between kinetic and potential, going completely from one to the other as the system oscillates. So for the simple example of an object on a frictionless surface attached to a spring, as shown again (see), the motion starts with all of the energy stored in the spring. As the object starts to move, the elastic potential energy is converted to kinetic energy, becoming entirely kinetic energy at the equilibrium position. It is then converted back into *elastic potential energy* by the spring, the velocity becomes zero when the kinetic energy is completely converted, and so on. This concept provides extra insight here and in later applications of simple harmonic motion, such as alternating current circuits.



Energy in a Simple Harmonic Oscillator: The transformation of energy in simple harmonic motion is illustrated for an object attached to a spring on a frictionless surface. (a) The mass has achieved maximum displacement from equilibrium. All energy is potential energy. (b) As the mass passes through the equilibrium point with maximum speed all energy in the system is in kinetic energy. (c) Once again, all energy is in the potential form, stored in the compression of the spring (in the first panel the energy was stored in the extension of the spring). (d) Passing through equilibrium again all energy is kinetic. (e) The mass has completed an entire cycle.

The conservation of energy principle can be used to derive an expression for velocity v. If we start our simple harmonic motion with zero velocity and maximum displacement (x=X), then the total energy is:

$$\mathrm{E}=\frac{1}{2}\mathrm{kX}^2. \tag{1.3.42}$$

This total energy is constant and is shifted back and forth between kinetic energy and potential energy, at most times being shared by each. The conservation of energy for this system in equation form is thus:

$$\frac{1}{2}\mathrm{mv}^2+\frac{1}{2}\mathrm{kx}^2=\frac{1}{2}\mathrm{kX}^2. \tag{1.3.43}$$

Solving this equation for v yields:

$$\mathrm{v}=\pm\sqrt{\frac{\mathrm{k}}{\mathrm{m}}(\mathrm{X}^2-\mathrm{x}^2)}. \tag{1.3.44}$$

Manipulating this expression algebraically gives:

$$\mathrm{v}=\pm\sqrt{\frac{\mathrm{k}}{\mathrm{m}}}\mathrm{X}\sqrt{1-\frac{\mathrm{x}^2}{\mathrm{X}^2}}, \tag{1.3.45}$$

and so:

$$\mathrm{v}=\pm\mathrm{v}_{\max}\sqrt{1-\frac{\mathrm{x}^2}{\mathrm{X}^2}}, \tag{1.3.46}$$

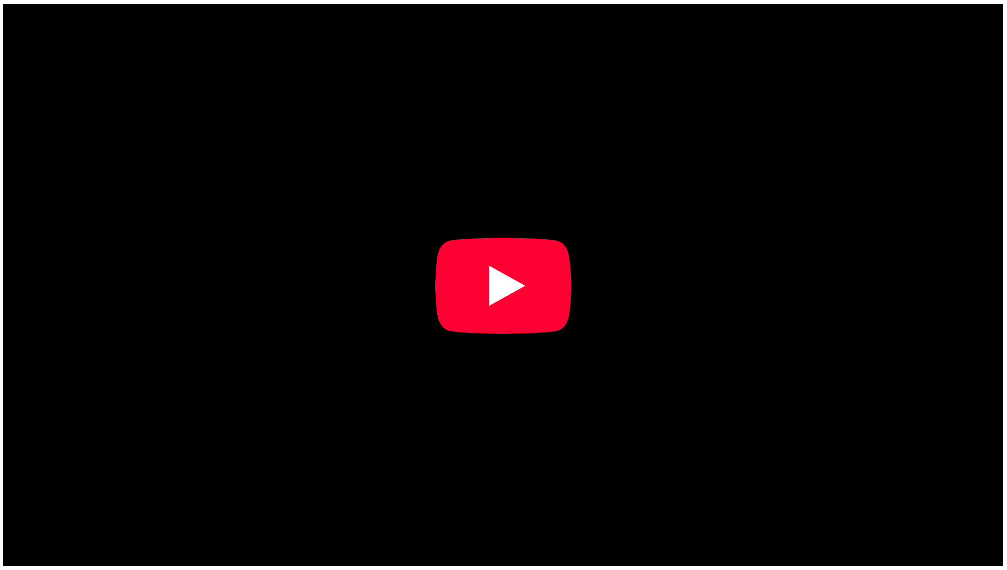
where:

$$\mathrm{v}_{\max}=\sqrt{\frac{\mathrm{k}}{\mathrm{m}}}\mathrm{X}. \tag{1.3.47}$$

From this expression, we see that the velocity is a maximum (v_{max}) at x=0. Notice that the maximum velocity depends on three factors. It is directly proportional to amplitude. As you might guess, the greater the maximum displacement, the greater the maximum velocity. It is also greater for stiffer systems because they exert greater force for the same displacement. This observation is seen in the expression for v_{max}; it is proportional to the square root of the force constant k. Finally, the maximum velocity is smaller for objects that have larger masses, because the maximum velocity is inversely proportional to the square root of m. For a given force, objects that have large masses accelerate more slowly.

A similar calculation for the simple pendulum produces a similar result, namely:

$$\omega_{\max}=\sqrt{\frac{\mathrm{g}}{\mathrm{L}}}\theta_{\max}. \tag{1.3.48}$$



Experience with a simple harmonic oscillator: A known mass is hung from a spring of known spring constant and allowed to oscillate. The time for one oscillation (period) is measured. This value is compared to a predicted value, based on the mass and spring constant.

Sinusoidal Nature of Simple Harmonic Motion

The solutions to the equations of motion of simple harmonic oscillators are always sinusoidal, i.e., sines and cosines.

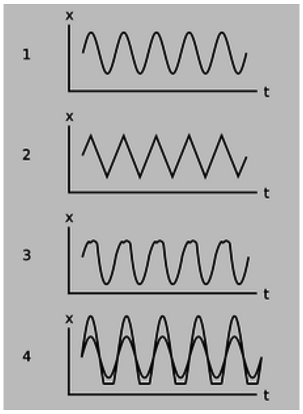
learning objectives

- Review factors responsible for the sinusoidal behavior of uniform circular motion

Sinusoidal Nature of Simple Harmonic Motion

Why are sine waves so common?

If the mass -on-a-spring system discussed in previous sections were to be constructed and its motion were measured accurately, its *x*–*t* graph would be a near-perfect sine-wave shape, as shown in. It is called a “sine wave” or “sinusoidal” even if it is a cosine, or a sine or cosine shifted by some arbitrary horizontal amount. It may not be surprising that it is a wiggle of this general sort, but why is it a specific mathematically perfect shape? Why is it not a sawtooth shape, like in (2); or some other shape, like in (3)? It is notable that a vast number of apparently unrelated vibrating systems show the same mathematical feature. A tuning fork, a sapling pulled to one side and released, a car bouncing on its shock absorbers, all these systems will exhibit sine-wave motion under one condition: the amplitude of the motion must be small.



Sinusoidal and Non-Sinusoidal Vibrations: Only the top graph is sinusoidal. The others vary with constant amplitude and period, but do no describe simple harmonic motion.

Hooke's Law and Sine Wave Generation

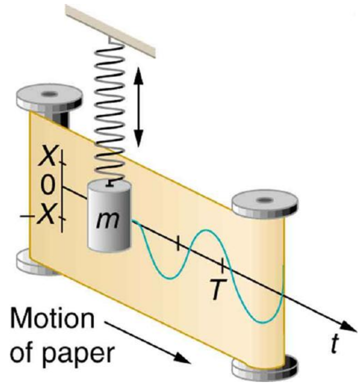
The key to understanding how an object vibrates is to know how the force on the object depends on the object's position. If a system follows Hooke's Law, the restoring force is proportional to the displacement. As touched on in previous sections, there exists a second order differential equation that relates acceleration and displacement.

$$F_{net} = m\frac{d^2x}{dt^2} = -kx. \tag{1.3.49}$$

When this general equation is solved for the position, velocity and acceleration as a function of time:

- $x(t) = A\cos(\omega t - \varphi)$
- $v(t) = \frac{dx}{dt} = -A\omega\sin(\omega t - \varphi)$
- $a(t) = \frac{d^2x}{dt^2} = -A\omega^2\cos(\omega t - \varphi)$

These are all sinusoidal solutions. Consider a mass on a spring that has a small pen inside running across a moving strip of paper as it bounces, recording its movements.

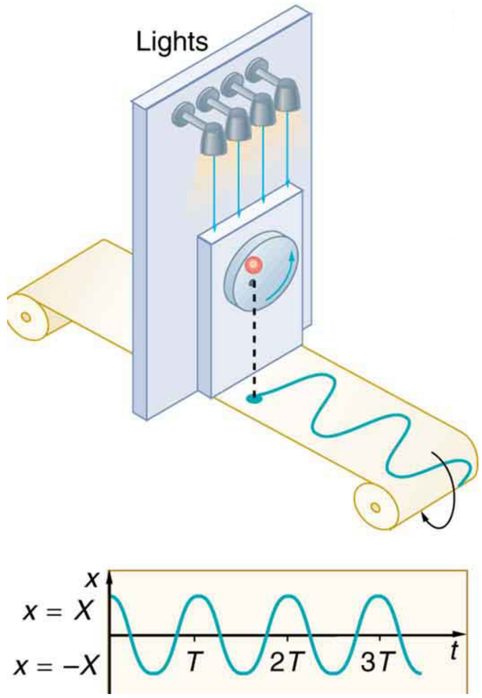


Mass on Spring Producing Sine Wave: The vertical position of an object bouncing on a spring is recorded on a strip of moving paper, leaving a sine wave.

The above equations can be rewritten in a form applicable to the variables for the mass on spring system in the figure.

- $x(t) = X\cos(\frac{2\pi t}{T})$
- $v(t) = -v_{max}\sin(\frac{2\pi t}{T})$
- $a(t) = -\frac{kX}{m}\cos(\frac{2\pi t}{T})$

Recall that the projection of uniform circular motion can be described in terms of a simple harmonic oscillator. Uniform circular motion is therefore also sinusoidal, as you can see from.



Sinusoidal Nature of Uniform Circular Motion: The position of the projection of uniform circular motion performs simple harmonic motion, as this wavelike graph of x versus t indicates.

Instantaneous Energy of Simple Harmonic Motion

The equations discussed for the components of the total energy of simple harmonic oscillators may be combined with the sinusoidal solutions for *x(t)*, *v(t)*, and *a(t)* to model the changes in kinetic and potential energy in simple harmonic motion.

The kinetic energy *K* of the system at time t is:

$$\mathrm{K(t)=\frac{1}{2}mv^2(t)=\frac{1}{2}m\omega^2A^2\sin^2(\omega t-\varphi)=\frac{1}{2}kA^2\sin^2(\omega t-\varphi)}. \tag{1.3.50}$$

The potential energy *U* is:

$$\mathrm{U(t)=\frac{1}{2}kx^2(t)==\frac{1}{2}kA^2\cos^2(\omega t-\varphi)}. \tag{1.3.51}$$

Summing *K(t)* and *U(t)* produces the total mechanical energy seen before:

$$\mathrm{E=K+U=\frac{1}{2}kA^2}. \tag{1.3.52}$$

Key Points

- Motion that repeats itself regularly is called periodic motion. One complete repetition of the motion is called a cycle. The duration of each cycle is the period.
- The frequency refers to the number of cycles completed in an interval of time. It is the reciprocal of the period and can be calculated with the equation f=1/T.
- Some motion is best characterized by the angular frequency (ω). The angular frequency refers to the angular displacement per unit time and is calculated from the frequency with the equation $\omega=2\pi\mathrm{f}$.
- If an object is vibrating to the right and left, then it must have a leftward force on it when it is on the right side, and a rightward force when it is on the left side.
- The restoring force causes an oscillating object to move back toward its stable equilibrium position, where the net force on it is zero.
- The simplest oscillations occur when the restoring force is directly proportional to displacement. In this case the force can be calculated as $\mathrm{F=-kx}$, where F is the restoring force, k is the force constant, and x is the displacement.

- The motion of a mass on a spring can be described as *Simple Harmonic Motion* (SHM): oscillatory motion that follows Hooke's Law.
- The period of a mass on a spring is given by the equation $T=2\pi\sqrt{\frac{m}{k}}$
- Simple harmonic motion is often modeled with the example of a mass on a spring, where the restoring force obey's Hooke's Law and is directly proportional to the displacement of an object from its equilibrium position.
- Any system that obeys simple harmonic motion is known as a simple harmonic oscillator.
- The equation of motion that describes simple harmonic motion can be obtained by combining Newton's Second Law and Hooke's Law into a second-order linear ordinary differential equation: $F_{net}=m\frac{d^2x}{dt^2}=-kx.$
- Uniform circular motion describes the movement of an object traveling a circular path with constant speed. The one-dimensional projection of this motion can be described as simple harmonic motion.
- In uniform circular motion, the velocity vector v is always tangent to the circular path and constant in magnitude. The acceleration is constant in magnitude and points to the center of the circular path, perpendicular to the velocity vector at every instant.
- If an object moves with angular velocity ω around a circle of radius r centered at the origin of the x-y plane, then its motion along each coordinate is simple harmonic motion with amplitude r and angular frequency ω.
- A simple pendulum is defined as an object that has a small mass, also known as the pendulum bob, which is suspended from a wire or string of negligible mass.
- When displaced, a pendulum will oscillate around its equilibrium point due to momentum in balance with the restoring force of gravity.
- When the swings (amplitudes) are small, less than about 15º, the pendulum acts as a simple harmonic oscillator with period $T=2\pi\sqrt{\frac{L}{g}}$, where L is the length of the string and g is the acceleration due to gravity.
- A physical pendulum is the generalized case of the simple pendulum. It consists of any rigid body that oscillates about a pivot point.
- For small amplitudes, the period of a physical pendulum only depends on the moment of inertia of the body around the pivot point and the distance from the pivot to the body's center of mass. It is calculated as:$T=2\pi\sqrt{\frac{I}{mgh}}$.
- The period is still independent of the total mass of the rigid body. However, it is not independent of the mass distribution of the rigid body. A change in shape, size, or mass distribution will change the moment of inertia and thus, the period.
- The sum of the kinetic and potential energies in a simple harmonic oscillator is a constant, i.e., $KE+PE=constant$. The energy oscillates back and forth between kinetic and potential, going completely from one to the other as the system oscillates.
- In a spring system, the conservation equation is written as: $\frac{1}{2}mv^2+\frac{1}{2}kx^2=constant=\frac{1}{2}kX^2$, where X is the maximum displacement.
- The maximum velocity depends on three factors: amplitude, the stiffness factor, and mass: $v_{max}=\sqrt{\frac{k}{m}}X$.
- For simple harmonic oscillators, the equation of motion is always a second order differential equation that relates the acceleration and the displacement. The relevant variables are x, the displacement, and k, the spring constant.
- Solving the differential equation above always produces solutions that are sinusoidal in nature. For example, $x(t), v(t), a(t), K(t),$ and $U(t)$ all have sinusoidal solutions for simple harmonic motion.
- Uniform circular motion is also sinusoidal because the projection of this motion behaves like a simple harmonic oscillator.

Key Terms

- **period**: The duration of one cycle in a repeating event.
- **angular frequency**: The angular displacement per unit time.
- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: f = n / t.
- **Restoring force**: A variable force that gives rise to an equilibrium in a physical system. If the system is perturbed away from the equilibrium, the restoring force will tend to bring the system back toward equilibrium. The restoring force is a function only of position of the mass or particle. It is always directed back toward the equilibrium position of the system
- **amplitude**: The maximum absolute value of some quantity that varies.
- **simple harmonic oscillator**: A device that implements Hooke's law, such as a mass that is attached to a spring, with the other end of the spring being connected to a rigid support, such as a wall.
- **oscillator**: A pattern that returns to its original state, in the same orientation and position, after a finite number of generations.

- **centripetal acceleration**: Acceleration that makes a body follow a curved path: it is always perpendicular to the velocity of a body and directed towards the center of curvature of the path.
- **uniform circular motion**: Movement around a circular path with constant speed.
- **simple pendulum**: A hypothetical pendulum consisting of a weight suspended by a weightless string.
- **physical pendulum**: A pendulum where the rod or string is not massless, and may have extended size; that is, an arbitrarily-shaped, rigid body swinging by a pivot. In this case, the pendulum's period depends on its moment of inertia around the pivot point.
- **mass distribution**: Describes the spatial distribution, and defines the center, of mass in an object.
- **elastic potential energy**: The energy stored in a deformable object, such as a spring.
- **dissipative forces**: Forces that cause energy to be lost in a system undergoing motion.
- **sinusoidal**: In the form of a wave, especially one whose amplitude varies in proportion to the sine of some variable (such as time).

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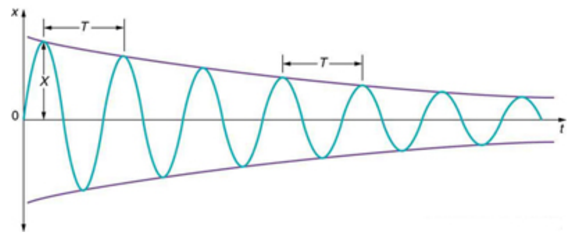
1.4: Damped and Driven Oscillations

learning objectives

- Describe the time evolution of the motion of the damped harmonic oscillator

The Physical Situation

The simple harmonic oscillator describes many physical systems throughout the world, but early studies of physics usually only consider ideal situations that do not involve friction. In the real world, however, frictional forces – such as air resistance – will slow, or dampen, the motion of an object. Sometimes, these dampening forces are strong enough to return an object to equilibrium over time.



Damped Harmonic Motion: Illustrating the position against time of our object moving in simple harmonic motion. We see that for small damping, the amplitude of our motion slowly decreases over time.

The simplest and most commonly seen case occurs when the frictional force is proportional to an object's velocity. Note that other cases exist which may lead to nonlinear equations which go beyond the scope of this example.

Consider an object of mass *m* attached to a spring of constant *k*. Let the damping force be proportional to the mass' velocity by a proportionality constant, *b,* called the *vicious damping coefficient.* We can describe this situation using Newton's second law, which leads to a second order, linear, homogeneous, ordinary differential equation. We simply add a term describing the damping force to our already familiar equation describing a simple harmonic oscillator to describe the general case of damped harmonic motion.

$$F_{net} = m\frac{d^2x}{dt^2} + b\frac{dx}{dt} + kx = 0 \tag{1.4.1}$$

$$= \frac{d^2x}{dt^2} + \frac{b}{m}\frac{dx}{dt} + \frac{k}{m}x = 0 \tag{1.4.2}$$

$$= \frac{d^2x}{dt^2} + \gamma\frac{dx}{dt} + \omega_0^2 x = 0 \tag{1.4.3}$$

$$\omega_0^2 = \frac{k}{m}, \gamma = \frac{b}{m} \tag{1.4.4}$$

This notation uses $\frac{d^2x}{dt^2}$, the acceleration of our object, $\frac{dx}{dt}$, the velocity of our object, ω_0, undamped angular frequency of oscillation, and ɣ, which we can call the damping ratio.

Solving the Differential Equation; Interpreting Results

We solve this differential equation for our equation of motion of the system, x(t). We assume a solution in the form of an exponential, where a is a constant value which we will solve for.

$$x(t) = e^{at} \tag{1.4.5}$$

Plugging this into the differential equation we find that there are three results for a, which will dictate the motion of our system. We can solve for a by using the quadratic equation.

$$F_{net} = a^2x + \gamma a x + \omega_0^2 x = 0 \tag{1.4.6}$$

$$= a^2 + \gamma a + \omega_0^2 = 0 \tag{1.4.7}$$

$$a = \frac{\gamma \pm \sqrt{\gamma^2 - 4\omega_0^2}}{2} \tag{1.4.8}$$

The physical situation has three possible results depending on the value of a, which depends on the value of what is under our radical. This expression can be positive, negative, or equal to zero which will result in overdamping, underdamping, and critical damping, respectively.

$\gamma^2 > 4\omega_0^2$ is the *Over Damped* case. In this case, the system returns to equilibrium by exponentially decaying towards zero. The system will not pass the equilibrium position more than once.

$\gamma^2 < 4\omega_0^2$ is the *Under Damped* case. In this case, the system oscillates as it slowly returns to equilibrium and the amplitude decreases over time. Figure 1 depicts an underdamped case.

$\gamma^2 = 4\omega_0^2$ is the*Critically Damped* case. In this case, the system returns to equilibrium very quickly without oscillating and without passing the equilibrium position at all.

Driven Oscillations and Resonance

Driven harmonic oscillators are damped oscillators further affected by an externally applied force.

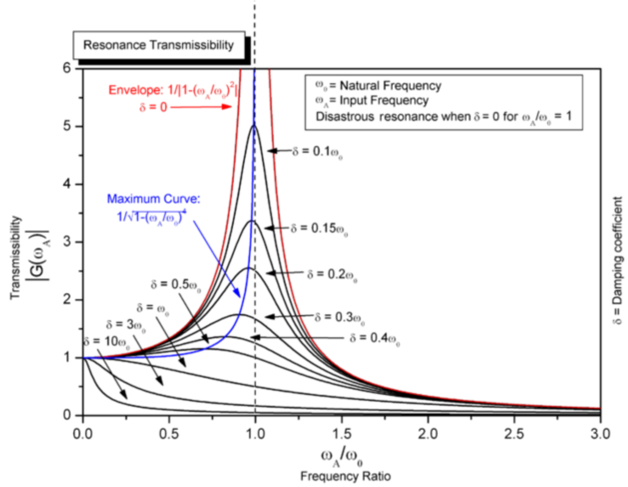
learning objectives

- Describe a driven harmonic oscillator as a type of damped oscillator

In classical mechanics, a harmonic oscillator is a system that, when displaced from its equilibrium position, experiences a restoring force, F, proportional to the displacement, $\mathrm{xF} \rightarrow = -\mathrm{k}\overrightarrow{\mathrm{x}}$ where k is a positive constant. If a frictional force (damping) proportional to the velocity is also present, the harmonic oscillator is described as a damped oscillator.

Driven harmonic oscillators are damped oscillators further affected by an externally applied force F(t). Newton's second law takes the form $\mathrm{F(t)} - \mathrm{kx} - \mathrm{c}\frac{\mathrm{dx}}{\mathrm{dt}} = \mathrm{m}\frac{\mathrm{d^2x}}{\mathrm{dt^2}}$. It is usually rewritten into the form $\frac{\mathrm{d^2x}}{\mathrm{dt^2}} + 2\zeta\omega_0\frac{\mathrm{dx}}{\mathrm{dt}} + \omega_0^2\mathrm{x} = \frac{\mathrm{F(t)}}{\mathrm{m}}$. This equation can be solved exactly for any driving force, using the solutions z(t) which satisfy the unforced equation: $\frac{\mathrm{d^2z}}{\mathrm{dt^2}} + 2\zeta\omega_0\frac{\mathrm{dz}}{\mathrm{dt}} + \omega_0^2\mathrm{z} = 0$, and which can be expressed as damped sinusoidal oscillations$\mathrm{z(t)} = \mathrm{Ae}^{-\zeta\omega_0\mathrm{t}}\sin\left(\sqrt{1-\zeta^2}\,\omega_0\mathrm{t}+\varphi\right)$ in the case where $\zeta \leq 1$. The amplitude A and phase φ determine the behavior needed to match the initial conditions. In the case $\zeta < 1$ and a unit step input with $\mathrm{x(0)} = 0$ the solution is: $\mathrm{x(t)} = 1 - \mathrm{e}^{-\zeta\omega_0\mathrm{t}}\frac{\sin\left(\sqrt{1-\zeta^2}\omega_0\mathrm{t}+\varphi\right)}{\sin(\varphi)}$ with phase φ given by $\cos\varphi = \zeta$. The time an oscillator needs to adapt to changed external conditions is of the order \(\mathrm{τ =\frac{1}{(ζ_0)}}\). In physics, the adaptation is called relaxation, and τ is called the relaxation time.

In the case of a sinusoidal driving force: $\frac{\mathrm{d^2x}}{\mathrm{dt^2}} + 2\zeta\omega_0\frac{\mathrm{dx}}{\mathrm{dt}} + \omega_0^2\mathrm{x} = \frac{1}{\mathrm{m}}\mathrm{F_0}\sin(\omega\mathrm{t})$, where $\mathrm{F_0}$ is the driving amplitude and ωω is the driving frequency for a sinusoidal driving mechanism. This type of system appears in AC driven RLC circuits (resistor-inductor-capacitor) and driven spring systems having internal mechanical resistance or external air resistance. The general solution is a sum of a transient solution that depends on initial conditions, and a steady state that is independent of initial conditions and depends only on the driving amplitude $\mathrm{F_0}$, driving frequency ωω, undamped angular frequency ω_0, and the damping ratio ζ. For a particular driving frequency called the resonance, or resonant frequency $\omega_\mathrm{r} = \omega_0\sqrt{1-2\zeta^2}$, the amplitude (for a given $\mathrm{F_0}$) is maximum. This resonance effect only occurs when $\zeta < 1/\sqrt{2}$, i.e. for significantly underdamped systems. For strongly underdamped systems the value of the amplitude can become quite large near the resonance frequency (see).



Resonance: Steady state variation of amplitude with frequency and damping of a driven simple harmonic oscillator.

Key Points

- To describe a damped harmonic oscillator, add a velocity dependent term, bx, where b is the *vicious dampingcoefficient*.
- Solve the differential equation for the equation of motion, x(t).
- Depending on the values of the damping coefficient and undamped angular frequency, the results will be one of three cases: an under damped system, an over damped system, or a critically damped system.
- Newton's second law takes the form $\mathrm{F(t)-kx-c\frac{dx}{dt}=m\frac{d^2x}{dt^2}}$ for driven harmonic oscillators.
- The resonance effect occurs only in the underdamped systems.
- For strongly underdamped systems the value of the amplitude can become quite large near the resonance frequency.

Key Terms

- **Under Damped**: "The condition in which damping of an oscillator causes it to return to equilibrium with the amplitude gradually decreasing to zero; system returns to equilibrium faster but overshoots and crosses the equilibrium position one or more times. "
- **Critically Damped**: "The condition in which the damping of an oscillator causes it to return as quickly as possible to its equilibrium position without oscillating back and forth about this position. "
- **Over Damped**: "The condition in which damping of an oscillator causes it to return to equilibrium without oscillating; oscillator moves more slowly toward equilibrium than in the critically damped system. "
- **oscillator**: A pattern that returns to its original state, in the same orientation and position, after a finite number of generations.
- **equilibrium**: The state of a body at rest or in uniform motion, the resultant of all forces on which is zero.
- **force**: A physical quantity that denotes ability to push, pull, twist or accelerate a body which is measured in a unit dimensioned in mass × distance/time² (ML/T^2): SI: newton (N); CGS: dyne (dyn)

- Driven oscillations. **Provided by**: Wikipedia. **Located at**: **en.Wikipedia.org/wiki/Driven_oscillations%23Driven_harmonic_oscillators**. **License**: ***CC BY-SA: Attribution-ShareAlike***
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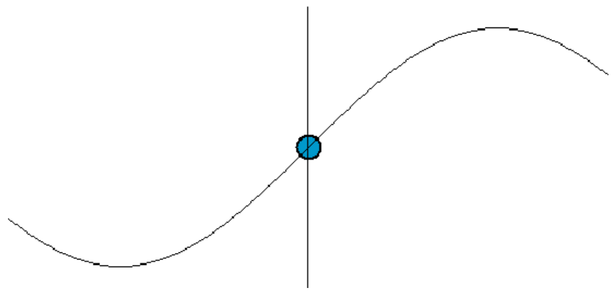
1.5: Waves

learning objectives

- Describe process of energy and mass transfer during wave motion

Vibrations and waves are extremely important phenomena in physics. In nature, oscillations are found everywhere. From the jiggling of atoms to the large oscillations of sea waves, we find examples of vibrations in almost every physical system. In physics a wave can be thought of as a disturbance or oscillation that travels through space-time, accompanied by a transfer of energy. Wave motion transfers energy from one point to another, often with no permanent displacement of the particles of the medium —that is, with little or no associated mass transport. They consist, instead, of oscillations or vibrations around almost fixed locations.

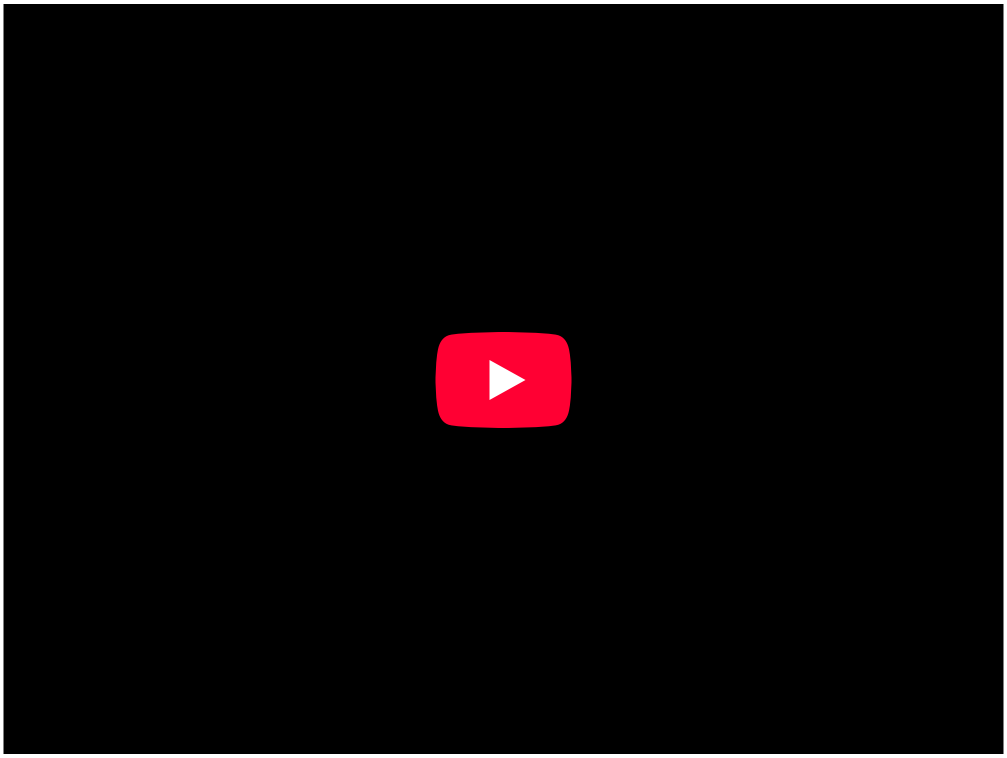
The emphasis of the last point highlights an important misconception of waves. Waves transfer energy not mass. An easy way to see this is to imagine a floating ball a few yards out to sea. As the waves propagate (i.e., travel) towards the shore, the ball will not come towards the shore. It may come to shore eventually due to the tides, current or wind, but the waves themselves will not carry the ball with them. A wave only moves mass perpendicular to the direction of propagation—in this case up and down, as illustrated in the figure below:

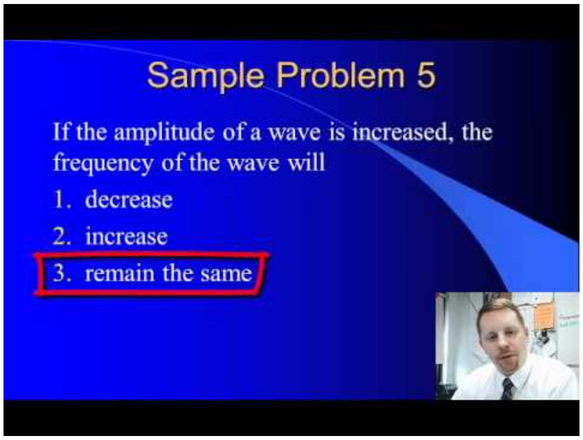


Wave motion: The point along the axis is analogous to the floating ball at sea. We notice that while it moves up and down it does not move in the direction of the wave's propagation.

A wave can be transverse or longitudinal depending on the direction of its oscillation. Transverse waves occur when a disturbance causes oscillations perpendicular (at right angles) to the propagation (the direction of energy transfer). Longitudinal waves occur when the oscillations are parallel to the direction of propagation. While mechanical waves can be both transverse and longitudinal, all electromagnetic waves are transverse. Sound, for example, is a longitudinal wave.

The description of waves is closely related to their physical origin for each specific instance of a wave process. For example, acoustics is distinguished from optics in that sound waves are related to a mechanical rather than an electromagnetic (light) wave transfer caused by vibration. Therefore, concepts such as mass, momentum, inertia or elasticity become crucial in describing acoustic (as distinct from optic) wave processes. This difference in origin introduces certain wave characteristics particular to the properties of the medium involved. In this chapter we will closely examine the difference between longitudinal and transverse waves along with some of the properties they possess. We will also learn how waves are fundamental in describing motion of many applicable physical systems.





The Wave Equation: A brief introduction to the wave equation, discussing wave velocity, frequency, wavelength, and period.

Transverse Waves

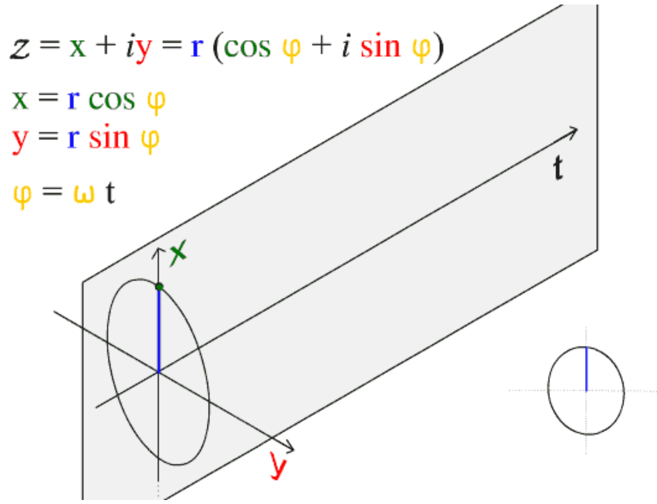
Transverse waves propagate through media with a speed $\vec{v}_w$ orthogonally to the direction of energy transfer.

learning objectives

- Describe properties of the transverse wave

A transverse wave is a moving wave that consists of oscillations occurring perpendicular (or right angled) to the direction of energy transfer. If a transverse wave is moving in the positive *x*-direction, its oscillations are in up and down directions that lie in the *y*–*z* plane. Light is an example of a transverse wave. For transverse waves in matter, the displacement of the medium is perpendicular to the direction of propagation of the wave. A ripple on a pond and a wave on a string are easily visualized transverse waves.

Transverse waves are waves that are oscillating perpendicularly to the direction of propagation. If you anchor one end of a ribbon or string and hold the other end in your hand, you can create transverse waves by moving your hand up and down. Notice though, that you can also launch waves by moving your hand side-to-side. This is an important point. There are two independent directions in which wave motion can occur. In this case, these are the *y* and *z* directions mentioned above. depicts the motion of a transverse wave. Here we observe that the wave is moving in *t* and oscillating in the *x*-*y* plane. A wave can be thought as comprising many particles (as seen in the figure) which oscillate up and down. In the figure we observe this motion to be in *x*-*y* plane (denoted by the red line in the figure). As time passes the oscillations are separated by units of time. The result of this separation is the sine curve we expect when we plot position versus time.

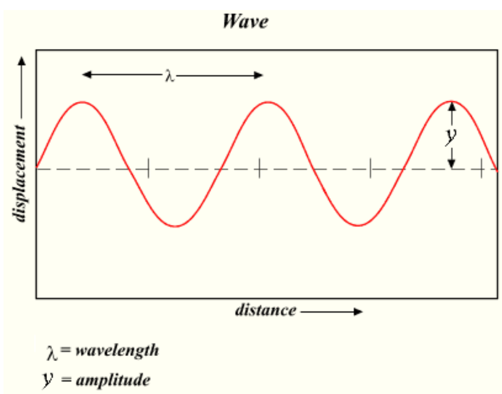


Sine Wave: The direction of propagation of this wave is along the t axis.

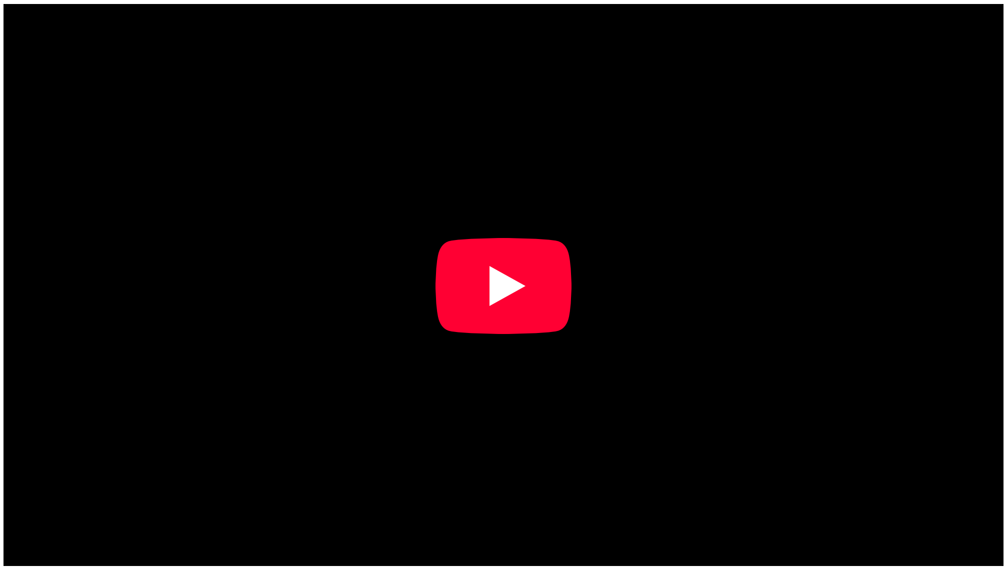
When a wave travels through a medium–i.e., air, water, etc., or the standard reference medium (vacuum)–it does so at a given speed: this is called the speed of propagation. The speed at which the wave propagates is denoted and can be found using the following formula:

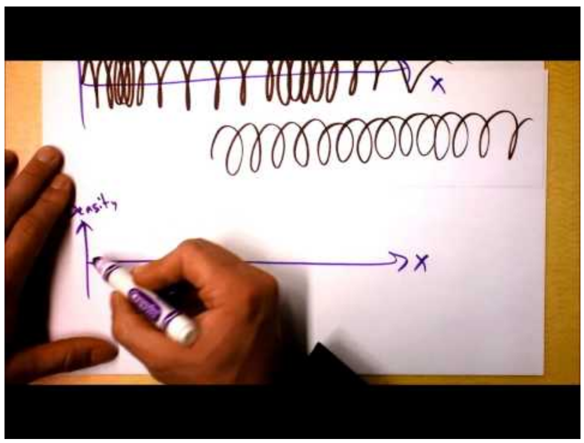
$$v = f\lambda \tag{1.5.1}$$

where *v* is the speed of the wave, *f* is the frequency , and is the wavelength. The wavelength spans crest to crest while the amplitude is 1/2 the total distance from crest to trough. Transverse waves have their applications in many areas of physics. Examples of transverse waves include seismic S (secondary) waves, and the motion of the electric (E) and magnetic (M) fields in an electromagnetic plane waves, which both oscillate perpendicularly to each other as well as to the direction of energy transfer. Therefore an electromagnetic wave consists of two transverse waves, visible light being an example of an electromagnetic wave.



Wavelength and Amplitude: The wavelength is the distance between adjacent crests. The amplitude is the 1/2 the distance from crest to trough.





Two Types of Waves: Longitudinal vs. Transverse: Even ocean waves!

Longitudinal Waves

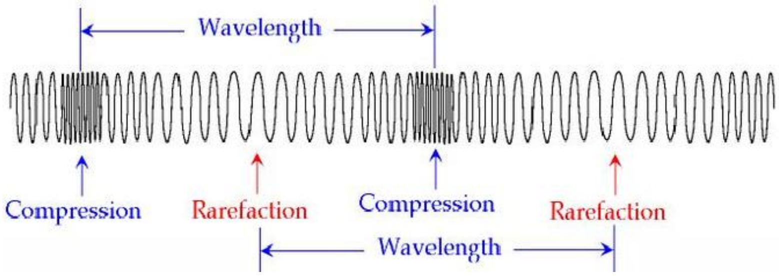
Longitudinal waves, sometimes called compression waves, oscillate in the direction of propagation.

learning objectives

- Give properties and provide examples of the longitudinal wave

Longitudinal Waves

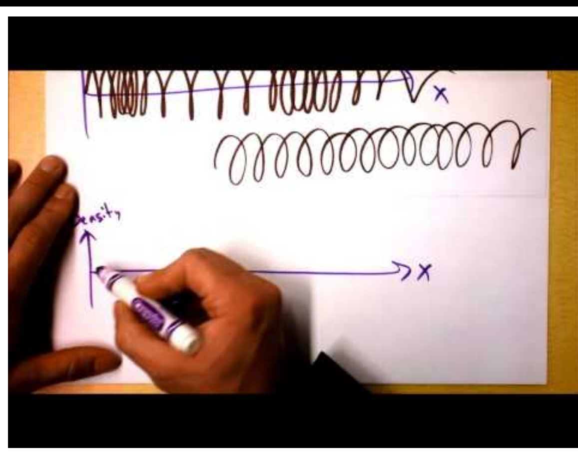
Longitudinal waves have the same direction of vibration as their direction of travel. This means that the movement of the medium is in the same direction as the motion of the wave. Some longitudinal waves are also called compressional waves or compression waves. An easy experiment for observing longitudinal waves involves taking a Slinky and holding both ends. After compressing and releasing one end of the Slinky (while still holding onto the end), a pulse of more concentrated coils will travel to the end of the Slinky.



Longitudinal Waves: A compressed Slinky is an example of a longitudinal wave. The wve propagates in the same direction of oscillation.

Like transverse waves, longitudinal waves do not displace mass. The difference is that each particle which makes up the medium through which a longitudinal wave propagates oscillates along the axis of propagation. In the example of the Slinky, each coil will oscillate at a point but will not travel the length of the Slinky. It is important to remember that energy, in this case in the form of a pulse, is being transmitted and not the displaced mass.

Longitudinal waves can sometimes also be conceptualized as pressure waves. The most common pressure wave is the sound wave. Sound waves are created by the compression of a medium, usually air. Longitudinal sound waves are waves of alternating pressure deviations from the equilibrium pressure, causing local regions of compression and rarefaction. Matter in the medium is periodically displaced by a sound wave, and thus oscillates. When people make a sound, whether it is through speaking or hitting something, they are compressing the air particles to some significant amount. By doing so, they create transverse waves. When people hear sounds, their ears are sensitive to the pressure differences and interpret the waves as different tones.



Two Types of Waves: Longitudinal vs. Transverse: Even ocean waves!

Water Waves

Water waves can be commonly observed in daily life, and comprise both transverse and longitudinal wave motion.

learning objectives

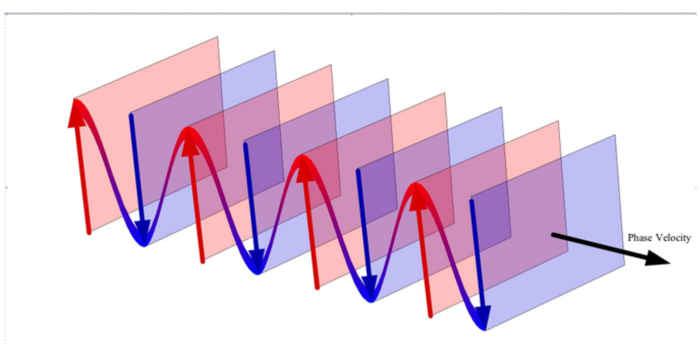
- Describe particle movement in water waves

Water waves, which can be commonly observed in our daily lives, are of specific interest to physicists. Describing detailed fluid dynamics in water waves is beyond the scope of introductory physics courses. Although we often observe water wave propagating in 2D, in this atom we will limit our discussion to 1D propagation.

Water waves: Surface waves in water

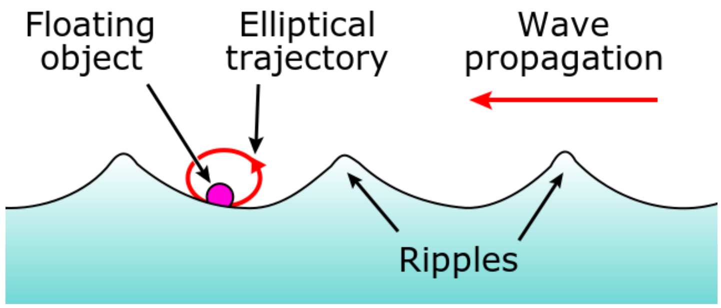
The uniqueness of water waves is found in the observation that they comprise both transverse and longitudinal wave motion. As a result, the particles composing the wave move in clockwise circular motion, as seen in. Oscillatory motion is highest at the surface and diminishes exponentially with depth. Waves are generated by wind passing over the surface of the sea. As long as the waves propagate slower than the wind speed just above the waves, there is an energy transfer from the wind to the waves. Both air pressure differences between the upwind and the lee side of a wave crest, as well as friction on the water surface by the wind (making the water to go into the shear stress), contribute to the growth of the waves.

In the case of monochromatic linear plane waves in deep water, particles near the surface move in circular paths, creating a combination of longitudinal (back and forth) and transverse (up and down) wave motions. When waves propagate in shallow water (where the depth is less than half the wavelength), the particle trajectories are compressed into ellipses. As the wave amplitude (height) increases, the particle paths no longer form closed orbits; rather, after the passage of each crest, particles are displaced slightly from their previous positions, a phenomenon known as Stokes drift.



Plane wave: We see a wave propagating in the direction of the phase velocity. The wave can be thought to be made up of planes orthogonal to the direction of the phase velocity.

Since water waves transport energy, attempts to generate power from them have been made by utilizing the physical motion of such waves. Although larger waves are more powerful, wave power is also determined by wave speed, wavelength, and water density. Deep water corresponds with a water depth larger than half the wavelength, as is a common case in the sea and ocean. In deep water, longer-period waves propagate faster and transport their energy faster. The deep-water group velocity is half the phase velocity. In shallow water for wavelengths larger than about twenty times the water depth (as often found near the coast), the group velocity is equal to the phase velocity. These methods have proven viable in some cases but do not provide a fully sustainable form of renewable energy to date.



Water waves: The motion water waves causes particles to follow clockwise circular motion. This is a result of the wave having both transverse and longitudinal properties.

Wavelength, Freqency in Relation to Speed

Waves are defined by its frequency, wavelength, and amplitude among others. They also have two kinds of velocity: phase and group velocity.

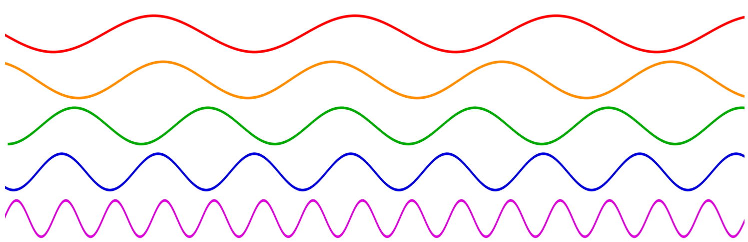
learning objectives

- Identify major characteristic properties of waves

Characteristics of Waves

Waves have certain characteristic properties which are observable at first notice. The first property to note is the amplitude. The amplitude is half of the distance measured from crest to trough. We also observe the wavelength, which is the spatial period of the wave (e.g. from crest to crest or trough to trough). We denote the wavelength by the Greek letter λλ.

The frequency of a wave is the number of cycles per unit time — one can think of it as the number of crests which pass a fixed point per unit time. Mathematically, we make the observation that,



Frequencies of different sine waves.: The red wave has a low frequency sine there is very little repetition of cycles. Conversely we say that the purple wave has a high frequency. Note that time increases along the horizontal.

$$\mathrm{f}=\frac{1}{\mathrm{T}} \tag{1.5.2}$$

where T is the period of oscillation. Frequency and wavelength can also be related-* with respects to a “speed” of a wave. In fact,

\[\mathrm{v=fλ}]

where v is called the wave speed, or more commonly,the phase velocity, the rate at which the phase of the wave propagates in space. This is the velocity at which the phase of any one frequency component of the wave travels. For such a component, any given phase of the wave (for example, the crest) will appear to travel at the phase velocity.

Finally, the group velocity of a wave is the velocity with which the overall shape of the waves’ amplitudes — known as the modulation or envelope of the wave — propagates through space. In, one may see that the overall shape (or “envelope”) propagates to the right, while the phase velocity is negative.

Fig 2: This shows a wave with the group velocity and phase velocity going in different directions. (The group velocity is positive and the phase velocity is negative.)

Energy Transportation

Waves transfer energy which can be used to do work.

learning objectives

- Relate direction of energy and wave transportation

Energy transportion is essential to waves. It is a common misconception that waves move mass. Waves carry energy along an axis defined to be the direction of propagation. One easy example is to imagine that you are standing in the surf and you are hit by a significantly large wave, and once you are hit you are displaced (unless you hold firmly to your ground!). In this sense the wave has done work (it applied a force over a distance). Since work is done over time, the energy carried by a wave can be used to generate power.

Water Wave: Waves that are more massive or have a greater velocity transport more energy.

Similarly we find that electromagnetic waves carry energy. Electromagnetic radiation (EMR) carries energy—sometimes called radiant energy—through space continuously away from the source (this is not true of the near-field part of the EM field). Electromagnetic waves can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. EMR also carries both momentum and angular momentum. These properties may all be imparted to matter with which it interacts (through work). EMR is produced from other types of energy when created, and it is converted to other types of energy when it is destroyed. The photon is the quantum of the electromagnetic interaction, and is the basic "unit" or constituent of all forms of EMR. The quantum nature of light becomes more apparent at high frequencies (or high photon energy). Such photons behave more like particles than lower-frequency photons do.

Electromagnetic Wave: Electromagnetic waves can be imagined as a self-propagating transverse oscillating wave of electric and magnetic fields. This 3D diagram shows a plane linearly polarized wave propagating from left to right.

In general, there is a relation of waves which states that the velocity (v) of a wave is proportional to the frequency (f) times the wavelength (λ):

$$\mathrm{v}=\mathrm{f}\lambda \tag{1.5.3}$$

We also know that classical momentum pp is given by p=mvp=mv which relates to force via Newton’s second law: $\mathrm{F}=\frac{\mathrm{dp}}{\mathrm{dt}}$

EM waves with higher frequencies carry more energy. This is a direct result of the equations above. Since $\mathrm{v}\propto\mathrm{f}$ we find that higher frequencies imply greater velocity. If velocity is increased then we have greater momentum which implies a greater force (it gets a little bit tricky when we talk about particles moving close to the speed of light, but this observation holds in the classical sense). Since energy is the ability of an object to do work, we find that for $\mathrm{W}=\mathrm{Fd}$ a greater force correlates to more energy transfer. Again, this is an easy phenomenon to experience empirically; just stand in front of a faster wave and feel the difference!

Key Points

- A wave can be thought of as a disturbance or oscillation that travels through space-time, accompanied by a transfer of energy.
- The direction a wave propagates is perpendicular to the direction it oscillates for transverse waves.
- A wave does not move mass in the direction of propagation; it transfers energy.
- Transverse waves oscillate in the z-y plane but travel along the x axis.
- A transverse wave has a speed of propagation given by the equation $\mathrm{v}=\mathrm{f}\lambda$.
- The direction of energy transfer is perpendicular to the motion of the wave.
- While longitudinal waves oscillate in the direction of propagation, they do not displace mass since the oscillations are small and involve an equilibrium position.
- The longitudinal ‘waves’ can be conceptualized as pulses that transfer energy along the axis of propagation.
- Longitudinal waves can be conceptualized as pressure waves characterized by compression and rarefaction.
- The particles which make up a water wave move in circular paths.
- If the waves move slower than the wind above them, energy is transfered from the wind to the waves.
- The oscillations are greatest on the surface of the wave and become weaker deeper in the fluid.
- The wavelength is the spatial period of the wave.
- The frequency of a wave refers to the number of cycles per unit time and is not to be confused with angular frequency.
- The phase velocity can be expressed as the product of wavelength and frequency.
- Waves which are more massive transfer more energy.
- Waves with greater velocities transfer more energy.
- Energy of a wave is transported in the direction of the waves transportation.

Key Terms

- **medium**: The material or empty space through which signals, waves or forces pass.
- **direction of propagation**: The axis along which the wave travels.
- **wave**: A moving disturbance in the energy level of a field.
- **wavelength**: The length of a single cycle of a wave, as measured by the distance between one peak or trough of a wave and the next; it is often designated in physics as λ, and corresponds to the velocity of the wave divided by its frequency.
- **trough**: A long, narrow depression between waves or ridges.
- **speed of propagation**: The speed at which a wave moves through a medium.
- **crest**: The ridge or top of a wave.
- **transverse wave**: Any wave in which the direction of disturbance is perpendicular to the direction of travel.
- **rarefaction**: a reduction in the density of a material, especially that of a fluid
- **Longitudinal**: Running in the direction of the long axis of a body.
- **compression**: to increase in density; the act of compressing, or the state of being compressed; compaction
- **phase velocity**: The velocity of propagation of a pure sine wave of infinite extent and infinitesimal amplitude.
- **group velocity**: The propagation velocity of the envelope of a modulated travelling wave, which is considered as the propagation velocity of information or energy contained in it.

- **plane wave**: A constant-frequency wave whose wavefronts (surfaces of constant phase) are infinite parallel planes of constant peak-to-peak amplitude normal to the phase velocity vector.
- **wave speed**: The absolute value of the velocity at which the phase of any one frequency component of the wave travels.
- **wavelength**: The length of a single cycle of a wave, as measured by the distance between one peak or trough of a wave and the next; it is often designated in physics as λ, and corresponds to the velocity of the wave divided by its frequency.
- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: $f = \frac{n}{t}$.
- **energy**: A quantity that denotes the ability to do work and is measured in a unit dimensioned in mass × distance^2/time^2 (ML^2/T^2) or the equivalent.
- **power**: A measure of the rate of doing work or transferring energy.
- **work**: A measure of energy expended in moving an object; most commonly, force times displacement. No work is done if the object does not move.

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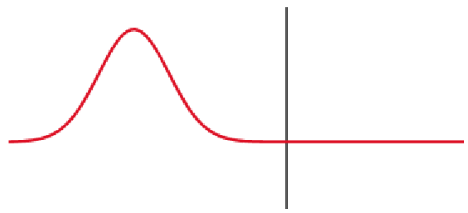
1.6: Wave Behavior and Interaction

learning objectives

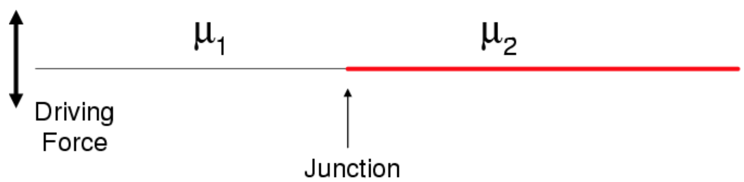
- Distinguish transmission and reflection phenomena

When the medium through which a wave travels suddenly changes, the wave often experiences partial transmission and partial refection at the interface. Reflection is a wave phenomenon that changes the direction of a wavefront at an interface between two different media so that the wavefront returns into the medium from which it originated. Transmission permits the passage of wave, with some or none of the incident wave being absorbed. Reflection and transmission often occur at the same time.



Partial Transmittance and Partial Reflectance: A wave experiences partial transmittance and partial reflectance when the medium through which it travels suddenly changes.

Consider a long string made by connecting two sub-strings with different density μ_1, μ_2. When the string is driven by an external force, partial reflection and transmission occur as in the figure above. For the incoming, reflected, and transmitted waves, we can try a solution of the following forms:



Two Strings With Different Density: Two strings with different density are connected and driven by an external driving force.

$$y_{inc} = A\cos(k_1 x - \omega t) \tag{1.6.1}$$
$$y_{ref} = B\cos(k_1 x + \omega t) \tag{1.6.2}$$
$$y_{trans} = C\cos(k_2 x - \omega t) \tag{1.6.3}$$

k_1 and k_2 are determined by the speed of the wave in each medium. We choose our coordinates such that the junction of two sub-strings is located at x=0. In choosing a trial solution for the waves, we assumed that the incident and transmitted waves travel to the right, while the reflected waves travel to the left. (This is why the '+' sign is chosen before ωtωt in the reflected wave. On the left side of the junction, we have

$$y_l = y_{inc} + y_{ref} = A\cos(k_1 x - \omega t). \tag{1.6.4}$$

On the right side, we have

$$y_r = y_{trans} = C\cos(k_2 x - \omega t) \tag{1.6.5}$$

We will impose additional restriction on the waves by applying "boundary conditions" at x=0. At the boundary x=0, the wave must be continuous and there should be no kinks in it. Thus we must have

$$y_l(x=0,t) = y_r(x=0,t) \tag{1.6.6}$$
$$\frac{\partial y_l(x,t)}{\partial x})_{x=0} = (\frac{\partial y_r(x,t)}{\partial x})_{x=0} \tag{1.6.7}$$

From the first equation, we get $A + B = C$. From the second equation, we get $A - B = (\frac{k_2}{k_1})C$.

Thus, we get the following result.

$$A = \frac{1}{2}(1 + \frac{k_2}{k_1})C \tag{1.6.8}$$

$$B = \frac{1}{2}(1 - \frac{k_2}{k_1})C \tag{1.6.9}$$

We can define the transmission (t) and reflection (r) coefficients as

$$t = \frac{C}{A} = \frac{2k_1}{k_1 + k_2}, r = \frac{B}{A} = \frac{k_1 - k_2}{k_1 + k_2}. \tag{1.6.10}$$

Superposition and Interference

A wave may have a complicated shape that can result from superposition and interference of several waves.

learning objectives

- Distinguish destructive and constructive interference and identify conditions that are required for the superposition of waves

Most waves do not look very simple. They look are often more complex than the simple water waves often considered in textbooks. Simple waves may be created by a simple harmonic oscillation, and thus have a sinusoidal shape. Complex waves are more interesting, even beautiful, but they look formidable. Most waves appear complex because they result from several simple waves adding together. Luckily, the rules for adding waves are quite simple.

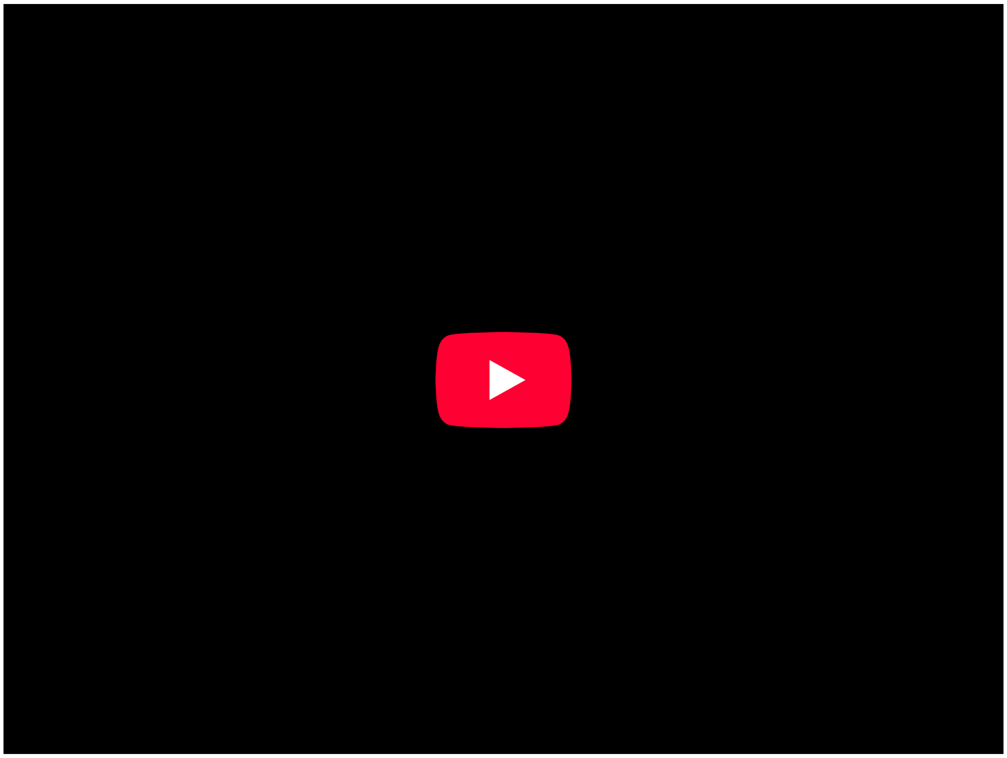
Complex Pattern of Waves: These waves result from the superposition of several waves from different sources, producing a complex pattern.

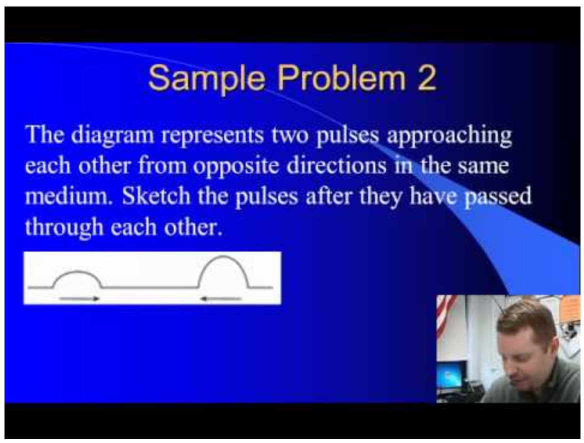
Superposition

When two or more waves arrive at the same point, they superimpose themselves on one another. More specifically, the disturbances of waves are superimposed when they come together—a phenomenon called superposition. Each disturbance corresponds to a force, and forces add. If the disturbances are along the same line, then the resulting wave is a simple addition of the disturbances of the individual waves—that is, their amplitudes add.

Interference

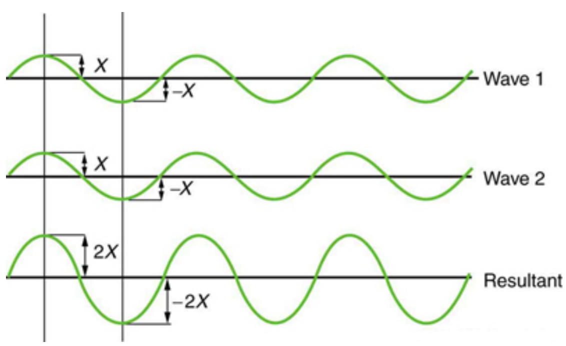
As a result of superposition of waves, interference can be observed. Interference is an effect caused by two or more waves.





Wave Interference: A brief introduction to constructive and destructive wave interference and the principle of superposition.

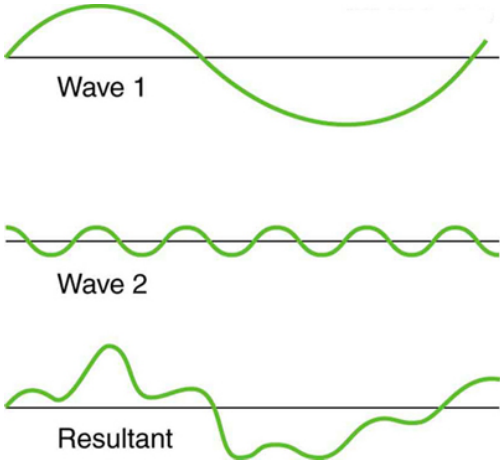
When two identical waves arrive at the same point exactly in phase the crests of the two waves are precisely aligned, as are the troughs. This superposition produces pure constructive interference. Because the disturbances add, constructive interference may produce a wave that has twice the amplitude of the individual waves, but has the same wavelength.



Constructive Interference: Pure constructive interference of two identical waves produces one with twice the amplitude, but the same wavelength.

If two identical waves that arrive exactly out of phase—that is, precisely aligned crest to trough—they may produce pure destructive interference. Because the disturbances are in the opposite direction for this superposition, the resulting amplitude may be zero for destructive interference, and the waves completely cancel.

While pure constructive and pure destructive interference do occur, they require precisely aligned identical waves. The superposition of most waves produces a combination of constructive and destructive interference and can vary from place to place and time to time. Here again, the disturbances add and subtract, producing a more complicated looking wave.



Superposition of Non-Identical Waves: Superposition of non-identical waves exhibits both constructive and destructive interference.

Standing Waves and Resonance

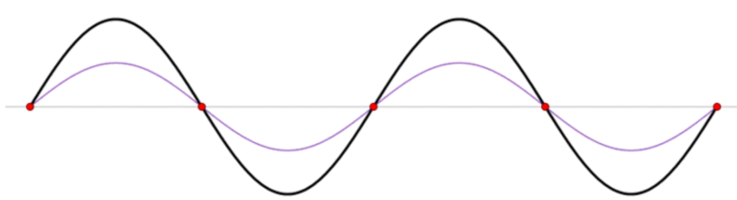
A standing wave is one in which two waves superimpose to produce a wave that varies in amplitude but does not propagate.

learning objectives

- Describe properties of a standing wave

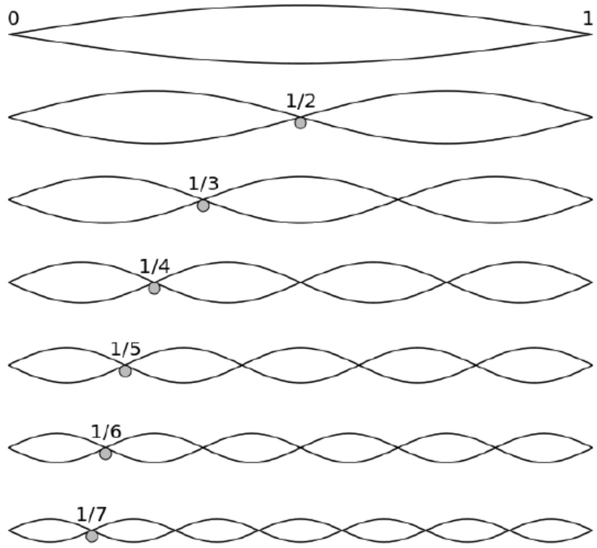
Standing Wave

Sometimes waves do not seem to move, but rather they just vibrate in place. These waves are formed by the superposition of two or more moving waves for two identical waves moving in opposite directions. The waves move through each other with their disturbances adding as they go by. If the two waves have the same amplitude and wavelength then they alternate between constructive and destructive interference. The resultant looks like a wave standing in place and, thus, is called a standing wave.



Standing Wave: A standing wave (black) depicted as the sum of two propagating waves traveling in opposite directions (red and blue).

Standing waves are found on the strings of musical instruments and are due to reflections of waves from the ends of the string. shows seven standing waves that can be created on a string that is fixed at both ends. Nodes are the points where the string does not move; more generally, nodes are where the wave disturbance is zero in a standing wave. The fixed ends of strings must be nodes, too, because the string cannot move there. The word antinode is used to denote the location of maximum amplitude in standing waves. Standing waves on strings have a frequency that is related to the propagation speed v_w of the disturbance on the string. The wavelength λ is determined by the distance between the points where the string is fixed in place.

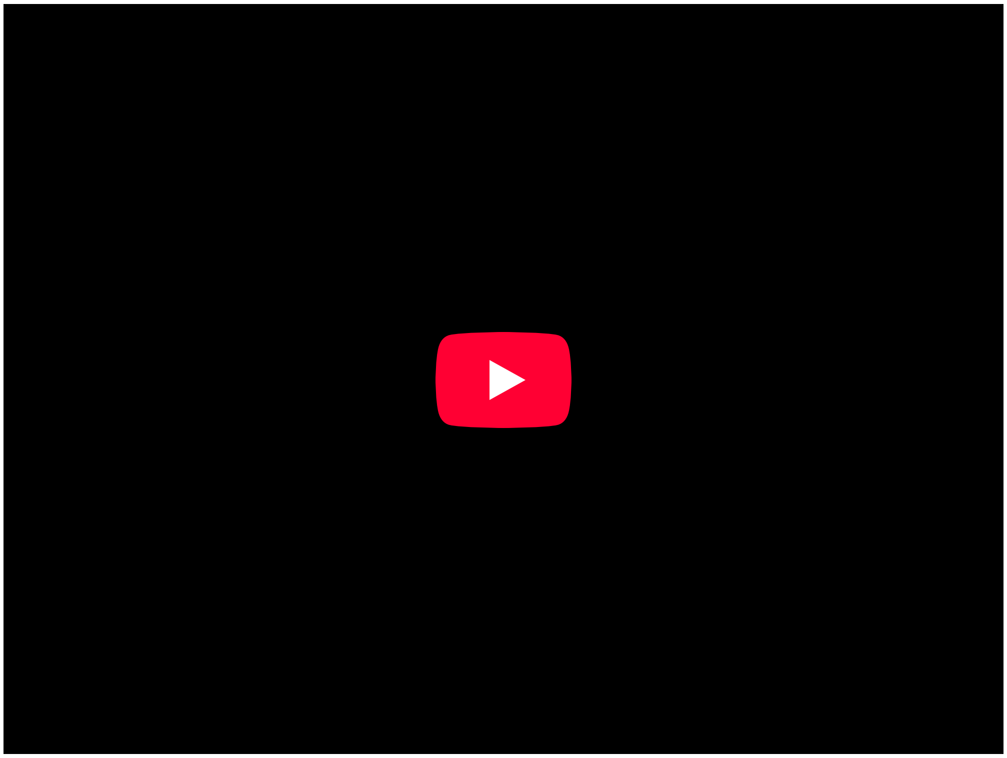


Standing Waves: Standing waves in a string, the fundamental mode and the first six overtones.

The lowest frequency, called the fundamental frequency, is thus for the longest wavelength, twice the length of the string. The overtones or harmonics are multiples of the fundamental frequency. shows the fundamental mode along with six overtones.

Resonance

A closer look at earthquakes provides evidence for conditions appropriate for resonance: standing waves, and constructive and destructive interference. A building may be vibrated for several seconds with a driving frequency matching that of the natural frequency of the vibration of the building—producing a resonance resulting in one building collapsing while neighboring buildings do not. Often buildings of a certain height are devastated while other taller buildings remain intact. The building height matches the condition for setting up a standing wave for that particular height. As the earthquake waves travel along the surface of Earth and reflect off denser rocks, constructive interference occurs at certain points. Often areas closer to the epicenter are not damaged while areas farther away are damaged.



Resonance: A brief overview of resonance, targeted toward introductory physics students.

Harmonic Wave Functions

When vibrations in the string are simple harmonic motion, waves are described by harmonic wave functions.

learning objectives

- Express relationship between the wave number and the wavelength, and frequency and period, of the harmonic wave function

In this Atom we shall consider wave motion resulting from harmonic vibrations and discuss harmonic transverse wave in the context of a string. We assume there is no loss of energy during transmission of wave along the string. This can be approximated when the string is light and taught. In such condition, if we oscillate the free end in harmonic manner, then the vibrations in the string are simple harmonic motion (SHM), perpendicular to the direction of wave motion. The amplitude of wave form remains intact through its passage along the string.

We know that a traveling wave function representing motion in x-direction has the form:

$$y(x,t) = Af(ax - bt). \tag{1.6.11}$$

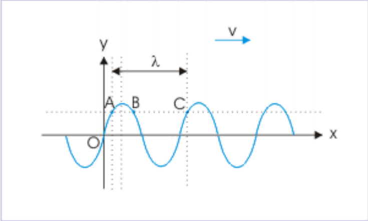
(Read our Atom on “Mathematical Representation of a Traveling Wave. “) For the case of harmonic vibration, we represent harmonic wave motion in terms of either harmonic sine or cosine function:

$$y(x,t) = A\sin(kx - \omega t). \tag{1.6.12}$$

Harmonic Oscillatory Properties

Each particle (or a small segment of string) vibrates in SHM. The particle attains the greatest speed at the mean position and reduces to zero at extreme positions. On the other hand, acceleration of the particle is greatest at extreme positions and zero at the mean position. The vibration of particle is represented by a harmonic sine or cosine function. For x=0:

$$y(x=0,t) = A\sin(\omega t) = A\sin(\omega t). \tag{1.6.13}$$



Harmonic Waves: Harmonic waves are described by sinusoidal functions. The wavelength is equal to linear distance between repetitions of transverse disturbance or phase.

Clearly, the displacement in y-direction is described by the bounded sine or cosine function. The important point here is to realize that oscillatory attributes (like time period, angular and linear frequency) of wave motion is same as that of vibration of a particle in transverse direction.

We know that time period in SHM is equal to time taken by the particle to complete one oscillation. It means that displacement of the particle from the mean position at a given position such as x=0 has same value after time period “T” for:

$\omega T = 2\pi$. Therefore, $\omega = \frac{2\pi}{T}$.

Similarly, displacement of the particle from the mean position at a given time such as t=0 has same value by change the position by “, where $k\lambda = 2\pi$. k is called wavenumber.

We can determine speed of the wave by noting that wave travels a linear distance ” in one period (T). Thus, speed of wave is given by:

$$v = \frac{\lambda}{T} = \frac{\omega}{k}. \tag{1.6.14}$$

Refraction

Refraction is a surface phenomenon that occurs as the change in direction of a wave due to a change in its medium.

learning objectives

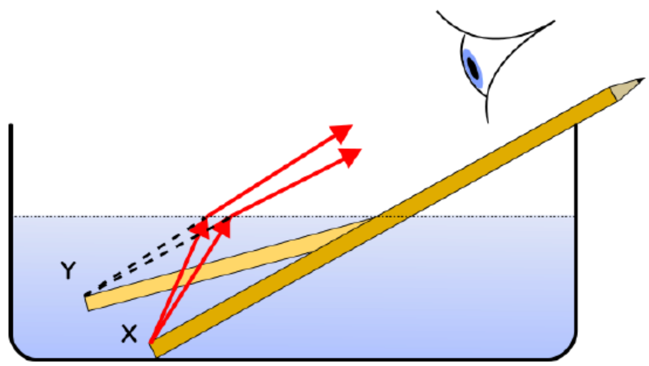
- Formulate the law of conservation of energy and momentum as it is applied to refraction

Refraction is the change in direction of a wave due to a change in its medium. Essentially, it is a surface phenomenon—mainly in governance to the law of conservation of energy and momentum. Due to change of medium, the phase velocity of the wave is changed but its frequency remains constant (most commonly observed when a wave passes from one medium to another at any angle other than 90° or 0°). Refraction of light is the most commonly observed phenomenon, but any type of wave can refract when it interacts with a medium (e.g., when sound waves pass from one medium into another or when water waves move into water of a different depth). Refraction is described by Snell’s law, which states that for a given pair of media and a wave with a single frequency, the ratio of the sines of the angle of incidence θ1 and angle of refraction θ2 is equivalent to the ratio of phase velocities (v_1/v_2) in the two media, or equivalently, to the opposite ratio of the indices of refraction (n_2/n_1):

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}. \tag{1.6.15}$$

In optics, refraction is a phenomenon that often occurs when waves travel from a medium with a given refractive index to a medium with another at an oblique angle. For example, a light ray will refract as it enters and leaves glass, assuming there is a change in refractive index. A ray traveling along the normal (perpendicular to the boundary) will change speed, but not direction. Refraction still occurs in this case. Understanding of refraction led to the invention of lenses and the refracting telescope.

Refraction can be seen when looking into a bowl of water, as illustrated in. Air has a refractive index of about 1.0003, and water has a refractive index of about 1.33. If a person looks at a straight object, such as a pencil or straw, placed partially in the water at a slant, the object appears to bend at the water's surface. This is due to the bending of light rays as they move from the water to the air. Once the rays reach the eye, the eye traces them back as straight lines (lines of sight). The lines of sight (shown as dashed lines) intersect at a higher position than where the actual rays originated (causing the pencil to appear higher and the water to appear shallower than they actually are).



Refraction in Water: An object (in this case a pencil) partially immersed in water looks bent due to refraction: the light waves from X change direction and so seem to originate at Y. (More accurately, for any angle of view, Y should be vertically above X, and the pencil should appear shorter, not longer as shown.)

Diffraction

Diffraction refers to various phenomena such as the bending of waves around obstacles and the spreading out of waves past small openings.

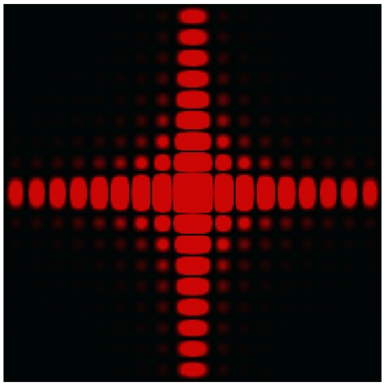
learning objectives

- Describe the phenomenon of diffraction, according to classical physics

Diffraction refers to various phenomena which occur when a wave encounters an obstacle. In classical physics, the diffraction phenomenon is described as the apparent bending of waves around small obstacles and the spreading out of waves past small openings. Similar effects occur when a light wave travels through a medium with a varying refractive index, or a sound wave travels through one with varying acoustic impedance.

Diffraction occurs with all waves, including sound waves, water waves, and electromagnetic waves such as visible light, X-rays and radio waves. As physical objects have wave-like properties (at the atomic level), diffraction also occurs with matter and can be studied according to the principles of quantum mechanics.

Diffraction effects are generally most pronounced for waves whose wavelengths are roughly similar to the dimensions of the diffracting objects. If the obstructing object provides multiple, closely-spaced openings, a complex pattern of varying intensity can result. This is due to the superposition, or interference, of different parts of a wave that travel to the observer by different paths. A good example would be diffraction gratings.



Intensity Pattern: Intensity pattern formed on a screen by diffraction from a square aperture.

The effects of diffraction are often seen in everyday life. The most striking examples of diffraction are those involving light. For example, the closely spaced tracks on a CD or DVD act as a diffraction grating to form the familiar rainbow pattern seen when looking at a disk. This principle can be extended to engineer a grating with a structure such that it will produce any diffraction pattern desired, like the hologram on a credit card. Diffraction in the atmosphere by small particles can cause a bright ring to be visible around a bright light source like the sun or the moon. A shadow of a solid object, using light from a compact source, shows small fringes near its edges. The speckle pattern which is observed when laser light falls on an optically rough surface is also a diffraction phenomenon. All these effects are a consequence of the fact that light propagates as a wave.

Mathematical Represenation of a Traveling Wave

The most general solution of the wave equation $\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$ is given as $u(x,t) = f(x+ct) + g(x-ct)$, where f and g are arbitrary functions.

learning objectives

- Formulate solution of the wave equation for a traveling wave

In general, one dimensional waves satisfy the 1D wave equation:

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}. \tag{1.6.16}$$

For example, a sinusoidal form

$$u(x,t) = A\sin(kx - \omega t) \tag{1.6.17}$$

is a solution of the wave equation for $c = \frac{\omega}{k}$. In this atom, we will obtain a general mathematical form of a traveling wave.

Solving the Wave Equation

First, we notice that any function u(x,t) satisfying

$$\frac{\partial u}{\partial t} = \pm c \frac{\partial u}{\partial x} (\text{Eq. } 1) \tag{1.6.18}$$

is a solution to the wave equation. To show this, note that

$$\frac{\partial^2 u}{\partial t^2} = \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial t}\right) = \pm c \frac{\partial}{\partial t}\left(\frac{\partial u}{\partial x}\right) \tag{1.6.19}$$

$$= \pm c \frac{\partial}{\partial x}\left(\frac{\partial u}{\partial t}\right) = c^2 \frac{\partial^2 u}{\partial x^2}. \tag{1.6.20}$$

In the middle, we used the equation 1 along with the fact that partial derivatives are interchangeable.

To solve the equation 1, let's introduce new variables: $\phi = x - ct, \psi = x + ct.$ From the chain rules,

$$\frac{\partial}{\partial t}=\frac{\partial \phi}{\partial t}\frac{\partial}{\partial \phi}+\frac{\partial \psi}{\partial t}\frac{\partial}{\partial \psi}=-c\frac{\partial}{\partial \phi}+c\frac{\partial}{\partial \psi}. \tag{1.6.21}$$

$$\frac{\partial}{\partial x}=\frac{\partial \phi}{\partial x}\frac{\partial}{\partial \phi}+\frac{\partial \psi}{\partial x}\frac{\partial}{\partial \psi}=\frac{\partial}{\partial \phi}+\frac{\partial}{\partial \psi}. \tag{1.6.22}$$

With the change of variables, the equation 1 becomes $\frac{\partial u_+}{\partial \phi}=0$ for the equation with the “+” sign and $\frac{\partial u_-}{\partial \psi}=0$ for the “-” sign. Therefore, we see that

$$u_+(\phi,\psi)=f(\psi), u_-(\phi,\psi)=g(\phi), \tag{1.6.23}$$

where f and g are arbitrary functions. Converting back to the original variables of x and t, we conclude that the solution of the original wave equation is

$$u(x,t)=f(x+ct)+g(x-ct). \tag{1.6.24}$$

f(x+ct) represents a left-going traveling wave, while g(x-ct) represents a right-going traveling wave. In other words, solutions of the 1D wave equation are sums of a left traveling function f and a right traveling function g. “Traveling” means that the shape of these individual arbitrary functions with respect to x stays constant, however the functions are translated left and right with time at the speed c. This solution was derived by Jean le Rond d’Alembert.

Boundary Condition

Any function that contains “x+ct” or “x-ct” can be a solution of the wave equation. The wave function is further determined by taking additional information, usually given as boundary conditions and some others. For example, in the case of a string in a guitar, we know that the wave has zero amplitude at both ends: u(x=0)=u(x=L)=0. Also, the shape of the function at an instance can be provided to determine the function.

Wave Equation in Two Dimensions: A solution of the wave equation in two dimensions with a zero-displacement boundary condition along the entire outer edge.

Energy, Intensity, Frequency, and Amplitude

The energy in a wave is proportional to its amplitude squared and the intensity of a wave is defined as power per unit area.

learning objectives

- Describe relationship between the energy and the amplitude, and energy and intensity, of a wave

All waves carry energy. This is seen in practical applications (e.g., in medicine), as well as effects in nature. Some examples of are:

- ultrasound used for deep-heat treatment of muscle strains
- a laser beam to burn away malignant tissue
- water waves that erode beaches
- earthquakes that topple cities

The amount of energy in a wave is related to its amplitude. Large-amplitude earthquakes produce large ground displacements, as seen in. Loud sounds have higher pressure amplitudes and come from larger-amplitude source vibrations than soft sounds. Large ocean breakers erode the shore more than small ones. More quantitatively, a wave is a displacement that is resisted by a restoring force. The larger the displacement x, the larger the force F=-kx needed to create it. Because work W is related to force multiplied by distance (Fx) and energy is put into the wave by the work done to create it, the energy in a wave is related to amplitude. In fact, a wave’s energy is directly proportional to its amplitude squared because:

Earthquake Destruction: The destructive effect of an earthquake is palpable evidence of the energy carried in these waves. The Richter scale rating of earthquakes is related to both their amplitude and the energy they carry.

$$W=\int F(x)dx=\frac{1}{2}kx^2. \tag{1.6.25}$$

The energy effects of a wave depend on time as well as amplitude. For example, the longer deep-heat ultrasound is applied, the more energy it transfers. Therefore, power is more appropriate than energy to describe the "intensity" of a wave. Waves can also be concentrated or spread out. Sunlight, for example, can be focused to burn wood. Earthquakes "spread out" so they do less damage the farther they spread from their source. In both cases, changing the area the waves cover has important effects. All these pertinent factors are included in the definition of intensity I as power (P) per unit area:

$$I=\frac{P}{A}, \tag{1.6.26}$$

where P is the power carried by the wave through area A.

Energy vs. Frequency

In classic wave theory, energy of a wave doesn't depend on the frequency of the wave. However, this is not the case in the microscopic world, as shown in experiments on photoelectric effects (see our Atom on "Photoelectric Effect"). As Einstein postulated to explain photoelectric effects, a quantum of light (photon) carries a specific amount of energy proportional to the frequency of light. Although you can increase the number of photons by increasing the intensity of a beam, the energy of individual photons in the beam is determined by the frequency of the beam.

Key Points

- Reflection is a wave phenomenon that changes the direction of a wavefront at an interface between two different media so that the wavefront returns into the medium from which it originated.
- At the boundary, a wave must be continuous and there should be no kinks in it.
- By imposing boundary conditions, we can solve wave equation and get the form of the waves. Reflection and transmission coefficients are defined as ratio of reflected/transmitted amplitudes and the incoming amplitude.
- The disturbances of waves are superimposed when they come together—a phenomenon called superposition.
- As a result of superposition of waves, inteference can be observed. Interference is an effect caused by two or more waves. Waves can interfere constructively or destructively.
- The superposition of most waves produces a combination of constructive and destructive interference and can vary from place to place and time to time.
- If two waves with the same amplitude and wavelength travel in opposite directions they alternate between constructive and destructive interference. The resultant looks like a wave standing in place and, thus, is called a standing wave.
- Nodes are points of no motion in standing waves. An antinode is the location of maximum amplitude of a standing wave.
- During an earthquake, buildings with a certain height may collapse more easily. This occurs when the building height matches the condition for setting up a standing wave for that particular height.
- We represent harmonic wave motion in terms of either harmonic sine or cosine function: $y(x,t)=A\sin(kx-\omega t)$.
- k and ω in the harmonic wave functinon are related to wavelength and period as follows: $k=\frac{2\pi}{\lambda}, \omega=\frac{2\pi}{T}$.
- The speed of a harmonic wave is given by ω/k.
- Refraction is mainly in governance to the law of conservation of energy and momentum. Due to change of medium, the phase velocity of the wave is changed but its frequency remains constant.

- Refraction is described by Snell's law, which states that for a given pair of media and a wave with a single frequency, $\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$.
- An object partially immersed in water looks bent due to refraction.
- Diffraction is a wave phenomenon. It occurs with all waves, including sound waves, water waves, and electromagnetic waves such as visible light, X-rays and radio waves.
- Diffraction effects are generally most pronounced for waves whose wavelengths are roughly similar to the dimensions of the diffracting objects.
- The effects of diffraction are often seen in everyday life. All these effects are a consequence of the fact that light propagates as a wave.
- Any function u(x,t) satisfying $\frac{\partial u}{\partial t} = \pm c\frac{\partial u}{\partial x}$ is a solution the wave equation. To solve this new equation, we introduced new variables $\phi = x - ct, \psi = x + ct$.
- The solutions of the 1D wave equation are sums of a left traveling function and a right traveling function.
- The wave function is further determined by taking additional information, usually given as boundary conditions and some others.
- The energy effects of a wave depend on the amplitude and duration (time) of the wave. Waves can also be concentrated or spread out. Considering all these factors, intensity is defined as power per unit area.
- In the classical wave theory, energy of a wave doesn't depend on the frequency of the wave. However, the energy of individual photons in a beam is determined by the frequency of the beam.
- Wave's energy is directly proportional to its amplitude squared.

Key Terms

- **boundary condition**: A set of restraints at the boundaries, used to solve a differential equation.
- **superposition**: The summing of two or more field contributions occupying the same space.
- **interference**: An effect caused by the superposition of two systems of waves, such as a distortion on a broadcast signal due to atmospheric or other effects.
- **constructive interference**: Occurs when waves interfere with each other crest to crest and the waves are exactly in phase with each other.
- **destructive interference**: Occurs when waves interfere with each other crest to trough (peak to valley) and are exactly out of phase with each other.
- **resonance**: The increase in the amplitude of an oscillation of a system under the influence of a periodic force whose frequency is close to that of the system's natural frequency.
- **simple harmonic motion**: (SHM) — Oscillating motion (as of a pendulum) in which the acceleration of the oscillator has an equal magnitude but opposite direction to the displacement of it from the equilibrium position.
- **Snell's law**: A formula used to describe the relationship between the angles of incidence and refraction.
- **refractive index**: The ratio of the speed of light in air or vacuum to that in another medium.
- **wave equation**: An important second-order linear partial differential equation for the description of waves such as sound waves, light waves, and water waves.
- **Restoring force**: If the system is perturbed away from the equilibrium, the restoring force will tend to bring the system back toward equilibrium. The restoring force is a function only of position of the mass or particle. It is always directed back toward the equilibrium position of the system.An example is the action of a spring. An idealized spring exerts a force that is proportional to the amount of deformation of the spring from its equilibrium length, exerted in a direction to oppose the deformation. Pulling the spring to a greater length causes it to exert a force that brings the spring back toward its equilibrium length. The amount of force can be determined by multiplying the spring constant of the spring by the amount of stretch.
- **ultrasound**: Sound with a frequency greater than the upper limit of human hearing; approximately 20 kilohertz.
- **photoelectric effects**: In photoelectric effects, electrons are emitted from matter (metals and non-metallic solids, liquids or gases) as a consequence of their absorption of energy from electromagnetic radiation.

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1.7: Waves on Strings

learning objectives

- Calculate the speed of a wave on a string

When studying waves, it is helpful to use a string to observe the physical properties of waves visually. Imagine you are holding one end of a string, and the other end is secured and the string is pulled tight. Now, if you were to flick the string either up and down. The wave that occurs due to this motion is called a transverse wave. A transverse wave is defined as a wave where the movement of the particles of the medium is perpendicular to the direction of the propagation of the wave. Figure 1 shows this in a diagram. In this case, the medium through which the waves propagate is the rope. The wave traveled from one end to the other, while the rope moved up and down.

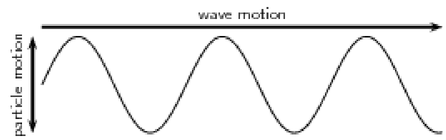


Figure 1: In transverse waves, the media the wave is traveling in moves perpendicular to the direction of the wave.

Wave Properties

Transverse waves have what are called peaks and troughs. The peak is the crest, or top point of the wave and the trough is the valley or bottom point of the wave. Refer to Figure 2 for a visual representation of these terms.The amplitude is the maximum displacement of a particle from its equilibrium position.Wavelength, usually denoted with a lambda (λ) and measured in meters, is the distance from either one peak to the next peak, or one trough to the next trough.Period, usually denoted as T and measured in seconds, is the time it takes for two successive peaks, or one wavelength, to pass through a fixed point.Frequency, *f*, is the number of wavelengths that pass through a given point in 1 second. Frequency is measured by taking the reciprocal of a period: $\mathrm{f} = \frac{1}{\mathrm{T}}$

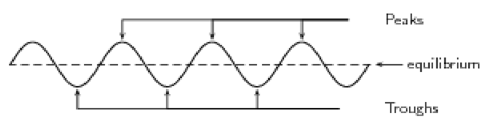


Figure 2: Peaks are the top most points of the waves and troughs are the bottom, or valleys of the waves.

Speed of a Wave on a String

Velocity is found by dividing the distance traveled by the time it took to travel that distance. In waves, this is found by dividing the wavelength by the period: v=λTv=λTWe can take the inverse proportionality to period and frequency and apply it to this situation:

$$\mathrm{v} = \frac{\lambda}{\mathrm{T}} \tag{1.7.1}$$

$$\mathrm{v} = \lambda \frac{1}{\mathrm{T}} \tag{1.7.2}$$

$$\mathrm{v} = \lambda \mathrm{f} \tag{1.7.3}$$

Speed of a Wave on a Vibrating String

Another example of waves on strings are of the waves on vibrating strings, such as in musical instruments. Pianos and guitars both use vibrating strings to produce music. In these cases, the frequency is what characterizes the pitch and therefore the note. The speed of a wave on this kind of string is proportional to the square root of the tension in the string and inversely proportional to the square root of the linear density of the string:$\mathrm{v} = \sqrt{\frac{\mathrm{T}}{\mu}}$

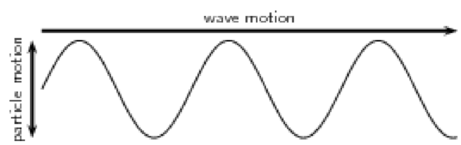
Reflections

When transverse waves in strings meet one end, they are reflected, and when the incident wave meets the reflected wave, interference occurs.

> **learning objectives**
>
> - Explain when a standing wave occurs

Overview

Imagine you are holding one end of a string, and the other end is secured and the string is pulled tight. Now, if you were to flick the string either up and down. The wave that occurs due to this motion is called a transverse wave. A transverse wave is defined as a wave where the movement of the particles of the medium is perpendicular to the direction of the propagation of the wave. shows this in a diagram. In this case, the medium through which the waves propagate is the rope. The wave traveled from one end to the other, while the rope moved up and down.



Transverse Wave: Diagram of a transverse wave. The wave motion moves perpendicular to the medium it is traveling in.

Properties of Waves

- Transverse waves have what are called peaks and troughs. The peak is the crest, or top point of the wave and the trough is the valley or bottom point of the wave.
- The amplitude is the maximum displacement of a particle from its equilibrium position.
- Wavelength, usually denoted with a lambda (λ) and measured in meters, is the distance from either one peak to the next peak, or one trough to the next trough.
- Period, usually denoted as T and measured in seconds, is the time it takes for two successive peaks, or one wavelength, to pass through a fixed point.
- Frequency, f, is the number of wavelengths that pass through a given point in 1 second. Frequency is measured by taking the reciprocal of a period: $f = \frac{1}{T}$
- Transverse waves can occur while being fixed at the end point or while being free at the end point.

Reflections of Transverse Waves

The way in which a transverse wave reflects depends on whether or not it is fixed at both ends. First we will look at waves that are fixed at both ends:

shows an image of a transverse wave that is reflected from a fixed end. When a transverse wave meets a fixed end, the wave is reflected, but inverted. This swaps the peaks with the troughs and the troughs with the peaks.

Transverse Wave With a Fixed End Point: A transverse wave that is fixed at the end point. The reflected wave is inverted.

is an image of a transverse wave on a string that meets a free end. The wave is reflected, but unlike a transverse wave with a fixed end, it is not inverted.

Transverse Wave With a Free End: When a transverse wave meets a free end, it is reflected.

Standing Waves

When either of the two scenarios of wave reflection occurs, the incident wave meets the reflected wave. These waves move past each other in opposite directions, causing interference. When these two waves have the same frequency, the product of this is called the standing waves. Standing waves appear to be standing still, hence the name. To understand how standing waves occur, we can analyze them further: When the incident wave and reflected wave first meet, both waves have an amplitude is zero. As the waves continue to move past each other, they continue to interfere with each other either constructively of destructively.

As you may remember from previous atoms, when waves are completely in phase and interfere with each other constructively, they are amplified, and when they are completely out of phase and interfere destructively they cancel out. As the waves continue to move past each other, and are reflected from the opposite end, they continue to interfere both ways, and a standing wave is produced.

Every point in the medium containing a standing wave oscillates up and down and the amplitude of the oscillations depends on the location of the point. When we observe standing waves on strings, it looks like the wave is not moving and standing still. The principle of standing waves is the basis of resonance and how many musical instruments get their sound. The points in a standing wave that appear to remain flat and do not move are called nodes. The points which reach the maximum oscillation height are called antinodes.

Key Points

- The type of wave that occurs in a string is called a transverse wave. In a transverse wave, the wave direction is perpendicular the the direction that the string oscillates in.
- The period of a wave is indirectly proportional to the frequency of the wave: $\mathrm{T}=\frac{1}{\mathrm{f}}$.
- The speed of a wave is proportional to the wavelength and indirectly proportional to the period of the wave: $\mathrm{v}=\frac{\lambda}{\mathrm{T}}$.
- This equation can be simplified by using the relationship between frequency and period:$\mathrm{v}=\lambda\mathrm{f}$.
- When a transverse wave on a string is fixed at the end point, the reflected wave is inverted from the incident wave. When a transverse wave on a string is free at the end point, the reflected wave is not inverted from the incident wave.
- A standing wave occurs when an incident wave meets a reflected wave on a string.
- The points in a standing wave that appear to remain flat and do not move are called nodes. The points which reach the maximum oscillation height are called antinodes.
- Every point in the medium containing a standing wave oscillates up and down and the amplitude of the oscillations depends on the location of the point.
- A standing wave has some points that remain flat due to destructive interference. These are called antinodes.
- The points on a standing wave that have reached maximum oscillation do so from constructive interference, and are called nodes.

Key Terms

- **transverse wave**: Any wave in which the direction of disturbance is perpendicular to the direction of travel.
- **oscillate**: To swing back and forth, especially if with a regular rhythm.
- **amplitude**: The maximum absolute value of some quantity that varies.
- **standing wave**: A wave form which occurs in a limited, fixed medium in such a way that the reflected wave coincides with the produced wave. A common example is the vibration of the strings on a musical stringed instrument.
- **transverse wave**: Any wave in which the direction of disturbance is perpendicular to the direction of travel.

CHAPTER OVERVIEW

2: Sound

Topic hierarchy

2.1: Introduction

learning objectives

- Explain how humans can characterize sound

Before delving too far into the physics of calculating sound waves (studying things like the Doppler Effect, for example), lets address some basics of sound. Sound is a wave—a longitudinal wave of pressure that travels through compressible medias (i.e., solid, liquid, gaseous, or made of plasma). There is no sound in a vacuum; by definition, a vacuum is a space free of any particles or matter. Thus there in a vacuum, there is no media through which sound waves can travel. Following are some characteristics of sound:

- Sound travels in longitudinal waves. When drawn these are also called sinusoidal waves, a visual example of which is shown in (we will cover this in more detail in a different section).
- Sound waves have frequency; that is, the pitch of sounds goes up or down.
- The amplitude of a sound determines its volume (loudness).
- Tone is a measure of the quality of a sound wave.
- Sound travels faster in a hot meduim, or in a solid. It also travels faster at sea level (where air pressure is higher).
- Sound intensity is the energy transmitted over a certain area. Intensity is a measure of the sound's frequency.
- Ultrasound uses sound waves with high frequencies to see things normally hard to detect, like tumors. Animals, like bats and dolphins, use ultrasound (echolocation) to navigate and locate things. Ships also use a similar technique (known as SONAR) to locate things underwater. (This point will be discussed further in a more advanced Atom.)

Sound Perception

Every sound wave has properties that define its frequency, such as wavelength, amplitude and intensity. Calculating these properties is outside the scope of this atom and will be addressed later. For now, it is important to know the basics of sound. As with light waves, sound frequencies have a range. Each living creature has a different level of sound perception. For example, consider the following examples of sound ranges (in Hz, Hertz):

- Humans 20 – 20,000 Hz
- Dogs 50 – 45,000 Hz
- Bats 20 – 120,000 Hz

By this comparison, humans have a relatively low sound perception.

Sound Speed

Breaking the Sound Barrier: This familiar image is of a plane that is moving faster than the speed of sound.

As mentioned previously, the speed at which sound travels depends on the media through which the sound is traveling. It is much faster in a solid than in a liquid or gas. The general formula for calculating the speed of sound is given as:

$$\mathrm{c}=\sqrt{\frac{\mathrm{K}}{\rho}}, \tag{2.1.1}$$

where K is the coefficient of stiffness of the material (also called the Bulk modulus) and p is the density of the material. We will examine this further in another section. Generally, the expression 'faster than the speed of sound' refers to 344 m/s. is an image demonstrating a plane moving faster than the speed of sound. This general measurement is taken at sea level—at a temperature of 21 degrees Celsius under normal atmospheric conditions.

Frequency of Sound Waves

Frequency is the number of occurrences of a repeating event per unit of time. The perception of frequency is called pitch.

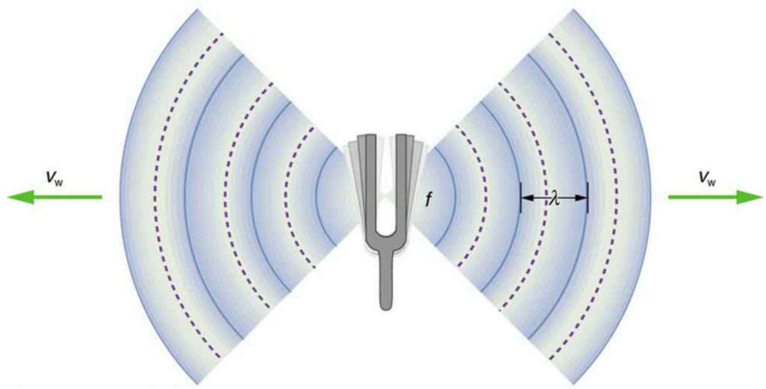
learning objectives

- Relate frequency with the wavelength and speed of sound

Sound waves, like all other waves, have a property called frequency. Frequency is the number of occurrences of a repeating event per unit of time. The perception of frequency is called pitch.

Frequency is dependent on wavelength and the speed of sound. It is calculated with the following equation: $f = \frac{v_s}{\lambda}$

This figure,, shows how the frequency is connected to wavelength.



Frequency: A sound wave emanates from a source vibrating at a frequency f, propagates at v, and has a wavelength λ.

Alternatively, you can use the frequency and the wavelength to find the speed of sound in a specific medium. Remember that sound travels at different speeds in different mediums; sound moves fastest through a solid. The following equation is used to find the specific speed of sound, and is often easier to use than the standard speed of sound equation: $vs=f*\lambda v\_s=f*\backslash lambda$

A period is the duration of one cycle of a repeating event, and is the reciprocal or inverse of the frequency. The following animation shows different frequencies and their periods, from lowest to highest.

Frequency Animation: Three flashing lights, from lowest frequency (top) to highest frequency (bottom). *f* is the frequency in hertz (*Hz*); or the number of cycles per second. *T* is the period in seconds (*s*); or the number of seconds per cycle. *T* and *f* are reciprocals.

Hertz

The SI unit of frequency is called a Hertz, denoted Hz. A hertz is defined as the number of cycles per second. For example, 100 Hz signifies 100 cycles per second.

Different species can hear different frequency ranges. Humans can only hear from 20 Hz to 20,000 Hz, while dogs can hear up to 60,000 Hz. Bats can hear the highest ranges, up to 120,000 Hz. Bats use this super hearing, or ultrasound, to locate objects and prey. By bouncing sound waves off of another object and hearing how long it takes for the sound to echo back to them, they are able to approximate the distance between themselves and the object. This is called echolocation.

Sound Production: Vibrating String and Air Columns

Sound can be produced by many different devices. A vibrating string or air column can both create music and have unique properties.

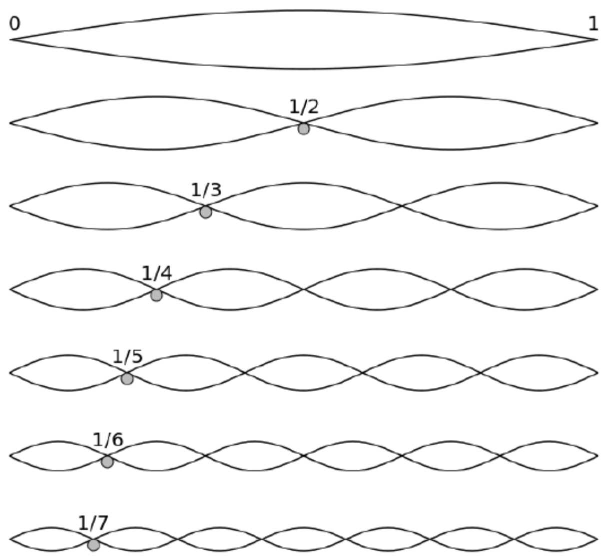
learning objectives

- Calculate the frequency of the sound wave produced by the string and a column of air

Sound can be produced in many ways, by many different instruments and devices. A vibrating string or air column can both make interesting music and it is good to understand the physics behind both.

Vibrating Strings

There are many instruments that produce sound based on strings. Guitars, cellos, pianos and many other examples. These sounds are produced by standing waves in the strings. These waves and their frequencies are constant, and therefor the sound and pitch produced by them is constant. This figure shows a visual of a standing wave in a string: The speed of the wave is proportional to the root of the string tension, and inversely proportional to the root of the string density, shown by the following equation $\mathrm{v}=\sqrt{\frac{\mathrm{T}}{\mu}}$ Pitch, and the way the sound is perceived depends on the frequency of the sound wave. Using the wave velocity, you can find the frequency using this equation: $\mathrm{f}=\frac{\mathrm{v}}{2\mathrm{L}}$, where L is the length of the string.

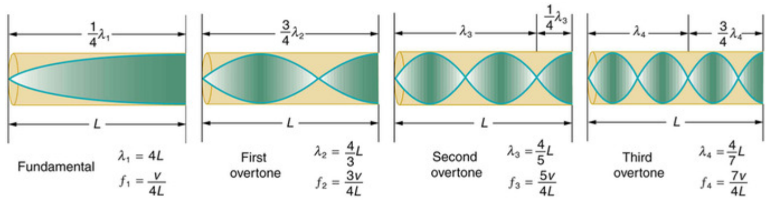


Standing Waves in a String: Vibration, standing waves in a string. The fundamental and the first 6 overtones form a harmonic series.

Air Columns

Many instruments make music by causing a vibration to a column of air in a resonator. These are usually called wind instruments. Examples of these are flutes, recorders, and saxophones. They are either open at both ends, or closed at one end and open at the other. The pitch of the sound is a function of the frequency. There are many factors that go into finding the frequency. Lets start with the tubes that are closed at one end and open at the other.

Closed Air Tubes:The maximum displacement of the air occurs at the open end of the tube, and is called the antinode. The air movement is constrained at the closed end, and there is no displacement, and this is called the node. The distance from the node to the antinode is 1/4 the length of one wavelength, and equal to the length of the tube, as shown in this equation:$\lambda = 4\mathrm{L}$This can also be seen in this figure: The frequency is equal to the speed of sound in the air divided by the wavelength, or:$\mathrm{f} = \frac{\mathrm{v_w}}{\lambda} = \frac{\mathrm{v_w}}{4\mathrm{L}}$, where $\mathrm{v_w}$ is the speed of sound in the air, which we learned how to find in a previous atom.



An Air column in a tube closed at one end: The fundamental and three lowest overtones for a tube closed at one end. All have maximum air displacements at the open end and none at the closed end.

Open Air tubes:Air tubes can also be open at both ends. They are very similar to the ones we talked about above, but there is an antinode at both ends, since they are both open, as shown in this figure: Since there is an antinode at both ends, we can see that the length of a wavelength is found by this equation: $\lambda = 2\mathrm{L}$ And the frequency can be found in the following equation:$\mathrm{f} = \frac{\mathrm{v_w}}{\lambda} = \frac{\mathrm{v_w}}{2\mathrm{L}}$

Quality of Sound

Sound quality is an assessment of accuracy or enjoyability of how a sound is perceived.

Skills to Develop

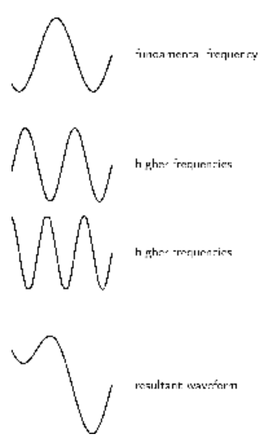
- Identify factors that influence the sound quality of a reproduction of music

Sound quality is an assessment of accuracy or enjoyability of how a sound is perceived. It can be measured objectively or subjectively. What is the difference? Objective measurement is taken when tools are used to gauge accuracy. Subjective measurement is more of an opinion. When human listeners hear a sound and compare it to another sound they have heard, and decide which one they enjoy more, this is a subjective measurement of sound quality.

Music Sound Quality

The quality of sound of live music is referred to as its tone. What makes this tone? Why does the same note being played on a piano sound different from that note played on a flute, or a guitar? When you hear a note, you mostly hear the fundamental frequency. But there are other harmonics present. You hear these, but they are much, much fainter than the fundamental, or main frequency. These are called *overtones*.

Each instrument has a different mix of these overtones, and this is why the sounds of similar notes sound different. The quality of this sound depends on these overtones to not take over what you are hearing. The overtones and fundamental frequency combine to make a unique frequency that you hear, which is illustrated in.



Sound Frequencies: The quality of a tone depends on its mixture of harmonics.

Reproduced Sound Quality

The sound quality of a reproduction of music depends on many factors. These include:

- Recording equipment
- Processing and mastering
- Reproduction equipment
- Listening environment

When you listen to a recording of music, you are hearing not only the music itself, but also any interference that may have been mistakenly recorded as well. The simplest form of digitally-stored audio is PCM.

As samples are placed closer together in time, higher frequencies can be reproduced. According to the sampling theorem, any signal with bandwidth *B* can be perfectly described by more than *2B* samples per second. Audio must be sampled at above 40kHz: 44.1kHz for CD recordings and 48kHz for DVD recordings.

The amount of space required to store PCM depends on the number of bits per sample, the number of samples per second, and the number of channels. For CD audio, this is 44,100 samples per second, 16 bits per sample, and 2 channels for stereo audio leading to 1,411,200 bits per second.

Speed of Sound

The speed of sound is is the distance traveled in a unit of time by a sound wave through an elastic medium, and is usually given as 344 m/s.

Skills to Develop

- Calculate the speed of sound from the properties of the media

Speed of Soud

The speed of sound is is the distance traveled in a unit of time by a sound wave through an elastic medium. This medium can be a solid, liquid, gas or even plasma. The speed of sound is dependent on the properties of the media the sound is travelling through. The general value given for the speed of sound is the speed of a sound wave in air, at sea level, at normal atmospheric pressure; that number is 344 m/s. However, this number is not constant. Sound travels faster in a solid than in a liquid, and faster in a liquid that in a gas.

Types of Sound Waves: Compression and Shear

There are two different kinds of sound waves: *compression waves* and *shear waves*. Compression waves can travel through any media, but shear waves can only travel through solids. The speed of a compression wave is determined by the media's compression capacity, shear modulus, and density, while the speed of the shear wave is only determined by the shear modulus and density. The shear modulus is a measurement of the elasticity or rigidity of a material. Calculating this is outside of the scope of this atom, but there are tables which tell you its value for materials.

Calculating the Speed of Sound

The speed of sound is usually denoted by cc, and a general equation can be used to calculate it. This is called the Newton-Laplace equation:c=√Kρc=KρK is the coefficient of stiffness, and p is the density of the media. From this equation, it is easy to see that the speed of sound will increase with stiffness and decrease with density. This is a very general equation, there are more specific derivations, for example:

The speed of sound in air at sea level is given by the following equation: $\mathrm{c_{air}} = 331\,\frac{\mathrm{m}}{\mathrm{s}} \times \sqrt{\frac{\mathrm{T}}{273\mathrm{K}}}$ T is the temperature in Kelvin.

Mach Number

You may have heard the term *Mach number* in relation to speed of space craft or jets before. This is a ratio of an object's speed in relation to the speed of sound. The Mach number is given by the following, dimensionless equation: $\mathrm{M} = \frac{\mathrm{v}}{\mathrm{a}}$ – Mach numberv – Velocity of object a – Speed of sound in medium. If something is travelling at the speed of sound, that would make the equation equal to 1, and can be denoted as Mach 1. shows a jet that is travelling at the speed of sound or faster. The *vapor cone* is made just before it reaches the speed of sound and is caused by a sudden drop in air pressure.

Faster than the Speed of Sound: This is a jet that is just about to break the sound barrier.

Key Points

- Sound travels in longitudinal sinusoidal waves.
- Humans can characterize sound by frequency, amplitude and tone.
- The speed at which sound travels depends on the media through which the sound is traveling. It can be calculated using: $c=\sqrt{\frac{K}{\rho}}$, where K is the coefficient of stiffness of the material (also called the Bulk modulus) and p is the density of the material.
- Frequency is dependent on wavelength and the speed of sound. It is calculated with the following equation: $f=\frac{v_s}{\lambda}$
- A period is the duration of one cycle of a repeating event, and is the reciprocal or inverse of the frequency.
- The SI unit of frequency is called a Hertz, denoted Hz. A hertz is defined as the number of cycles per second. For example, 100 Hz signifies 100 cycles per second.
- The frequency, and therefore the pitch of a string instrument depends on the velocity of the sound wave and the length of the string. The frequency is found by: $f=\frac{\sqrt{\frac{T}{\mu}}}{2L}$.
- Sound in a tube of air that is closed at one end is found by the following equation: $f=\frac{v_w}{\lambda}=\frac{v_w}{4L}$.
- Sound in a tube of air that is open at one end is found by the following equation: $f=\frac{v_w}{\lambda}=\frac{v_w}{2L}$.
- Objective measurement is taken when tools are used to gauge accuracy. Subjective measurement is more of an opinion. When human listeners hear a sound and compare it to another sound they have heard, and decide which one they enjoy more, this is a subjective measurement of sound quality.
- The quality of sound of live music is referred to as its tone. When you hear a note, you mostly hear the fundamental frequency. But there are other harmonics present. You hear these, but they are much, much fainter than the fundamental, or main frequency. These are called overtones.
- The sound quality of a reproduction of music depends on many factors. These include: recording equipment, processing and mastering,reproduction equipment, and even listening environment.
- Sound can travel through any compressible material. These media can be solid, liquid, gas, or even plasma.
- The speed of sound is dependent on the properties of the material it travels through. It will travel faster through a solid than a liquid, and faster through a liquid than a gas.
- The general number given for the speed of sound is calculated at sea level, in air, at normal atmospheric pressure. That value is 344 m/s.

Key Terms

- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: $f=\frac{n}{t}$.
- **Hertz**: Measurement of sound frequency.
- **media**: General term for different types of materials.
- **period**: The duration of one cycle in a repeating event.
- **node**: Point on a wave where there is no displacement.
- **antinode**: A region of maximum amplitude situated between adjacent nodes of a vibrating body, such as a string
- **Subjective measurement**: Based on a comparison to a previous experience, opinion.
- **Objective measurement**: Taken by tools to gauge accuracy.
- **elasticity**: The property by virtue of which a material deformed under the load can regain its original dimensions when unloaded
- **kelvin**: in the International System of Units, the base unit of thermodynamic temperature; 1/273.16 of the thermodynamic temperature of the triple point of water; symbolized as K

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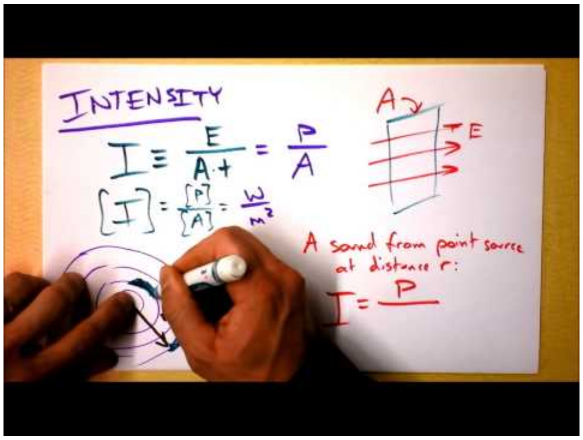
2.2: Sound Intensity and Level

learning objectives

- Calculate sound intensity from power

Overview of Intensity

Sound Intensity is the power per unit area carried by a wave. Power is the rate that energy is transferred by a wave.

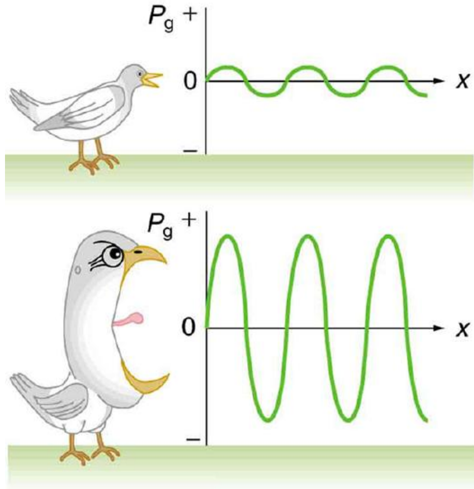


Sound Intensity and Decibels

The equation used to calculate this intensity, I, is:I$I = \frac{P}{A}$ Where P is the power going through the area, A. The SI unit for intensity is watts per meter squared or,Wm2Wm2. This is the general intensity formula, but lets look at it from a sound perspective.

Sound Intensity

Sound intensity can be found from the following equation: $I = \frac{\Delta p^2}{2\rho v_w}$. Δp – change in pressure, or amplitudeρ – density of the material the sound is traveling throughv_w – speed of observed sound.Now we have a way to calculate the sound intensity, so lets talk about observed intensity. The pressure variation, amplitude, is proportional to the intensity, So it is safe to say that the larger your sound wave oscillation, the more intense your sound will be. This figure shows this concept.



Sound Intensity: Graphs of the gauge pressures in two sound waves of different intensities. The more intense sound is produced by a source that has larger-amplitude oscillations and has greater pressure maxima and minima. Because pressures are higher in the greater-intensity sound, it can exert larger forces on the objects it encounters

Although the units for sound intensity are technically watts per meter squared, it is much more common for it to be referred to as decibels, dB. A decibel is a ratio of the observed amplitude, or intensity level to a reference, which is 0 dB. The equation for this is: \(\mathrm{β=10 \log _{10} \frac{I}{I_0}β}\) – decibel levelI – Observed intensityI_0– Reference intensity.For more on decibels, please refer to the Decibel Atom.

For a reference point on intensity levels, below are a list of a few different intensities:

- 0 dB, I = 1×10^{-12} –> Threshold of human hearing
- 10 dB, I = 1×10^{-11} –> Rustle of leaves
- 60 dB, I = 1×10^{-6} –> Normal conversation
- 100 dB, I = 1×10^{-2} –> Loud siren
- 160 dB, I = 1×10^{4}–> You just burst your eardrums

Human Perception of Sound

The study of human perception of sound is called psychoacoustics.

Skills to Develop

- Explain how frequency is perceived by humans

The study of the human perception of sound is called psychoacoustics. Many factors go into hearing, including wave properties, sensory and brain processes. First, the wave has to be made, and it has a specific wavelength and frequency. Then the sound wave reaches the human ear, and is processed through many areas. Finally, the sound wave makes it through the ear and to the human brain, where even more action happens. You might think that when something makes a noise that you hear it instantaneously but, in reality, it goes through many steps first.

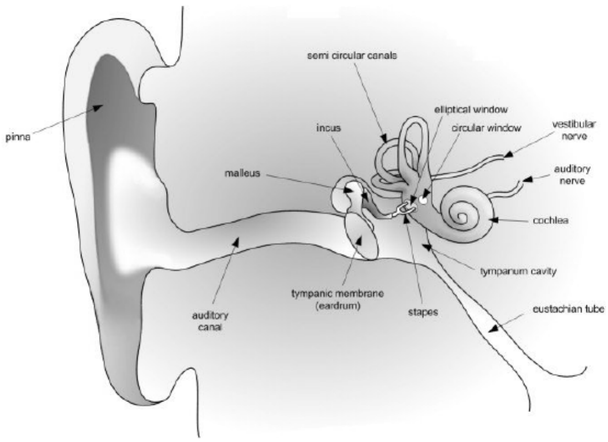
Wave Properties

We are not going to go into too much detail about the wave's physical properties, since it is out of the scope of this atom, but remember:

- Frequency is perceived by humans as pitch;
- The sound intensity is the amplitude;
- Humans can only hear a specific range of sound, usually from 20 Hz to 20,000 Hz;
- The factors that go into a sound are its intensity, frequency and overtones (which are like interference, or background noises).

The Human Ear

The human ear is made up of three main sections, as shown in:



The Human Ear: A detailed diagram of the human ear.

1. The outer ear
2. The middle ear
3. The inner ear

We are going to start where a sound wave would start and follow it on its journey from outside your ear all the way to your brain. When you look at someone's ear, you are really only seeing the pinna, the outer most portion of the ear. It collects and focuses the sound wave. The wave then goes through your ear canal to the eardrum. The sound waves cause the eardrum to vibrate. Then we are in the middle ear, which has three very, very small bones: the malleus, incus and stapes. These can also be referred to as the hammer, anvil and stirrup, respectively. These three bones transmit the signal to the elliptical window. This is the beginning of the inner ear. The sound waves are then transmitted from the elliptical window through the inner ear's semicircular canals, the cochlea, and the audio nerve, which is filled with fluid. This fluid is what allows the body to detect movements and maintain balance. Your cochlea is shaped like a snail, and is full of teeny tiny hairs. These hairs vibrate differently depending on the frequencies. These vibrations release electrical impulses to the auditory nerve and are then sent to your brain, where they are understood as sound. So while this seems to happen very quickly, sound waves have to travel a long way before you ever hear anything!

Decibels

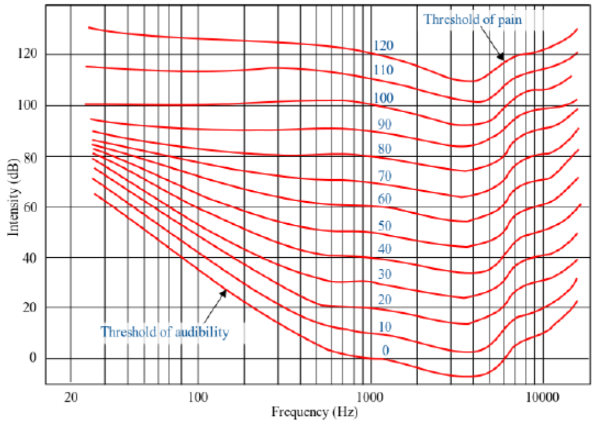
The decibel is a logarithmic unit used to quantify sound levels, by comparing a physical quantity to a reference level.

Skills to Develop

- Identify how decibel is quantified in acoustics

The decibel, dB, is commonly used to quantify sound levels, although it is not a unit of sound, but a unit of pressure. The decibel is a logarithmic unit that indicates the ratio if a physical quantity to a reference level. It is one tenth of a Bel, which was named after the inventor of the telephone, Alexander Graham Bell. The word decibell comes from the prefix, deci, that is 1/10 of the word it precedes For more information on how to convert units, refer to the unit conversion atom. Although the decibel can be used to talk about a number of different subjects, in this atom we are going to cover its use in acoustics and sound level.

In acoustics, the decibel is quantified relative to a reference which has been set at a sound pressure level of 20 micropascals, and is called a 0 dB. This reference level is a typical threshold of human hearing perception. The following equation is used to calculate the sound pressure level, or amplitude: $\mathrm{amplitude[dB]} = 20\log_{10}\frac{\mathrm{s}}{\mathrm{s_o}}$ $\mathrm{s_o}$ is the reference pressure which is 20 micropascals or 0 dB, and s is the observed sound pressure.The human ear has a standard sound threshold of 120 dB, which expressed logarithmically is around 10^{12}. This is a standard threshold, but it also depends on frequency. Loudness is a measure of sound intensity taking frequency into account, and is called a A-weighted decibel, dB(A), or a phon. This figure shows The Fletcher Munson Chart, which demonstrates the different sound frequencies and decibels that the human ear perceives as the same.



The Fletcher Munson Chart: The Fletcher-Munson equal-loudness contours. Phons are labelled in blue

Key Points

- Sound intensity can be found from the following equation: $\mathrm{I} = \frac{\Delta \mathrm{p}^2}{2\rho \mathrm{v_w}}$. Δ p – change in pressure, or amplitude ρ – density of the material the sound is traveling through v_w– speed of observed sound.
- The larger your sound wave oscillation, the more intense your sound will be.
- Although the units for sound intensity are technically watts per meter squared, it is much more common for it to be referred to as decibels, dB.
- Frequency is perceived by humans as pitch. The sound intensity is what humans can hear, and is generally only a specific range of sound, usually from 20 Hz to 20,000 Hz. The factors that go into a sound are its intensity, frequency and overtones (which are like interference or background noises).
- Your ear is made up of three major sections: the inner, middle and outer ear.
- Your cochlea, which is in your inner ear, not only transmits sound waves to your brain, but also contains a liquid that helps humans maintain their balance.
- In acoustics, the decibel is quantified relative to a reference which has been set at a sound pressure level of 20 micropascals, and is called a 0 dB.
- The following equation is used to calculate the sound pressure level, or amplitude: $\mathrm{amplitude}[\mathrm{dB}] = 20 \log_{10} \frac{\mathrm{s}}{\mathrm{s_o}}$. s_o is the reference pressure which is 20 micropascals or 0 dB, and s is the observed sound pressure.
- The human ear has a standard sound threshold of 120 dB, which expressed logarithmically is around 1012. This is a standard threshold, but it also depends on frequency. Loudness is a measure of sound intensity taking frequency into account, and is called a A-weighted decibel, dB(A), or a phon.

Key Terms

- **decibel**: A common measure of sound intensity that is one tenth of a bel on the logarithmic intensity scale. It is defined as $\mathrm{dB} = 10 \log_{10}(\mathrm{P_1}/\mathrm{P_2})$, where $\mathrm{P_1}$ and $\mathrm{P_2}$ are the relative powers of the sound.
- **amplitude**: The maximum absolute value of some quantity that varies.
- **eardrum**: A thin membrane that separates the outer ear from the middle ear and transmits sound from the air to the malleus.
- **cochlea**: The complex, spirally coiled, tapered cavity of the inner ear in which sound vibrations are converted into nerve impulses.
- **phon**: A unit of apparent loudness, equal in number to the intensity in decibels of a 1,000-hertz tone judged to be as loud as the sound being measured.

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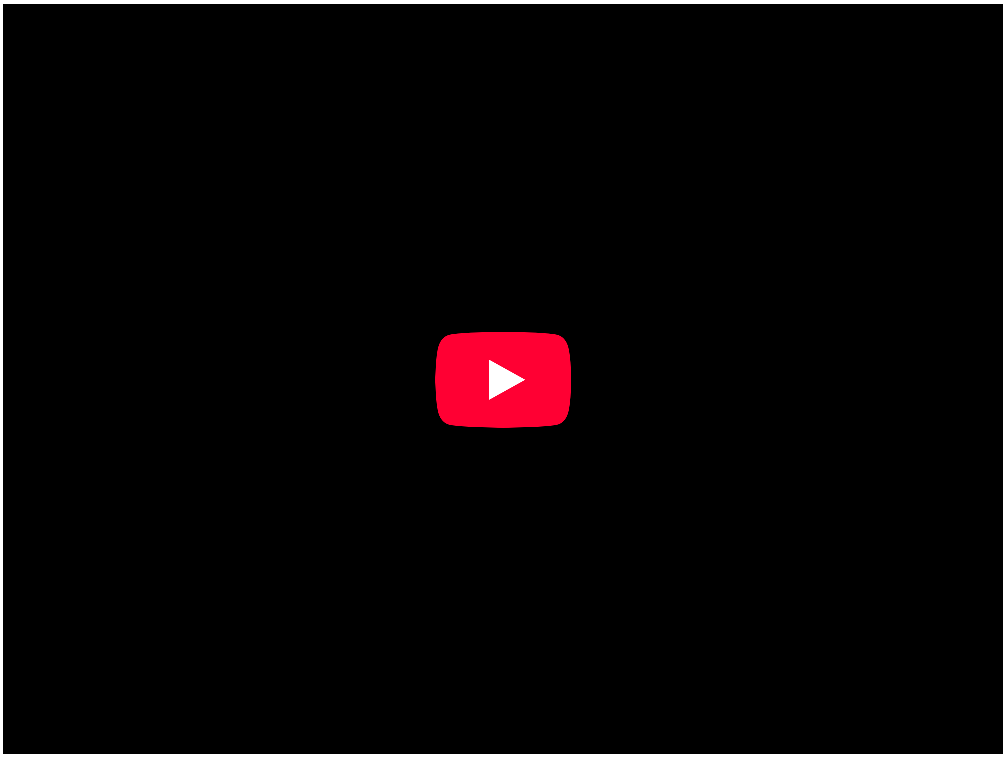
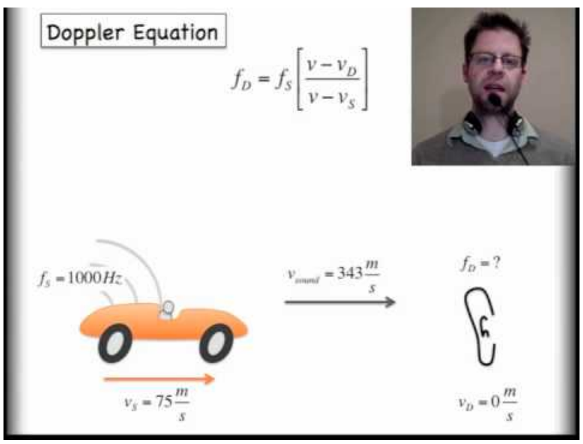
2.3: Doppler Effect and Sonic Booms

learning objectives

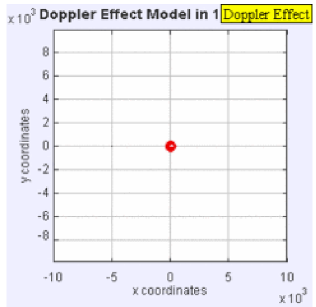
- Identify parameters required to calculate the frequency perceived by the observer moving towards the sound source

In this atom, we are going to cover the Doppler effect, but specifically when the observer is the one in motion.





Sound and the Doppler Effect: This video introduces sound waves. The first video describes the basics of sound while the second video looks at the Doppler Effect.



The Doppler Effect: The same sound source is radiating sound waves at a constant frequency in the same medium. However, now the sound source is moving to the right with a speed υs = 0.7 c (Mach 0.7). The wave-fronts are produced with the same frequency as before. However, since the source is moving, the centre of each new wavefront is now slightly displaced to the right. As a result, the wave-fronts begin to bunch up on the right side (in front of) and spread further apart on the left side (behind) of the source.

When the observer moves toward an sound source, each successive wave is encountered sooner than the previous wave. Thus, it will take just a little less time for the observer to hear the next one. Since the time between waves is reduced, the frequency is increased. Similarly if the observer is moving away from the sound source, the frequency, and therefor pitch, is decreased. While the frequency will change whether the observer or sound source is moving, it is easier to show with the sound source as the one moving. This figure demonstrated the sound source moving:

Unless the observer is moving directly towards the sound source, this angle needs to be taken into account when calculating the newly perceived frequency. Before we can start this calculation, we must know:

- The original sound wave frequency, f_0
- The velocity of the observer, v_r
- The speed of sound in the air, or medium, c
- The angle of the line of sight from the observer to the sound source, θθ

Although the sound waves are being emitted from the sound source at a uniform frequency, the observer is perceiving them differently. The equation for the perceived wave frequency is as follows: $f = \frac{c \pm v_{r,new}}{c} \times f_0$ And the equation for v_r, is: $v_{r,new} = v_r \cos\theta$ If the observer is moving towards the sound source, you are going to use a plus sign in front of the observers velocity. If the observer is moving away from sound source, you are going to use a negative sign in front of the observers velocity.

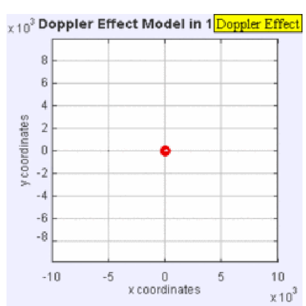
Moving Source

The Doppler effect is the apparent change in frequency of a wave when the observer and the source of the wave move relative to each other.

learning objectives

- Identify parameters required to calculate the perceived frequency of the sound source moving towards an observer

The Doppler Effect —When the Sound Source is in Motion



The Doppler Effect: The same sound source is radiating sound waves at a constant frequency in the same medium. However, now the sound source is moving to the right with a speed υs = 0.7 c (Mach 0.7). The wave-fronts are produced with the same frequency as before. However, since the source is moving, the centre of each new wavefront is now slightly displaced to the right. As a result, the wave-fronts begin to bunch up on the right side (in front of) and spread further apart on the left side (behind) of the source.

When the sound source moves toward an observer, each successive wave is emitted closer to the observer than the previous wave and takes just a little less time to reach the observer than the previous one. Since the time between waves is reduced, the frequency is increased. Similarly, if the sound source is moving away from the observer, the frequency (and therefore pitch) is decreased. While the frequency will change whether the observer or sound source is moving, the effect is more easily demonstrated by the sound source. This Doppler Effect is illustrated in.

Unless the observer is moving directly towards the sound source, this angle must be considered when calculating the newly perceived frequency. Before attempting this calculation, we must know:

- The original sound wave frequency, f_0
- The velocity of the observer, v_r
- The speed of sound in the air, or medium, c
- The angle of the line of sight from the observer to the sound source, θ

Although the sound waves are being emitted from the sound source at a uniform frequency, the observer is perceiving them differently. The equation for the perceived wave frequency is as follows: $f = \frac{c}{c \pm v_{s,new}} * f_0$ And the equation for v_s, is:

$$v_{s,new} = v_s \cos\theta \tag{2.3.1}$$

If the sound source is moving towards the observer, a plus sign is used in front of the sound source's velocity. If the sound source is moving away from the observer, then a negative sign is used in front of the sound source's velocity.

General Case

The Doppler effect is the apparent change in frequency of a wave when the observer and the source of the wave move relative to each other.

learning objectives

- Compare change in the frequency due to the doppler effect when the object in motion moves towards or away from the other object

Have you ever wondered why as a firetruck speeds by, the sound of the siren seems to change? Or where the very distinguishable sound at a race track comes from as the cars whisk by you? Well believe it or not, this is science! The name of this is called the Doppler effect, named for the scientist who discovered it. His name was Christian Doppler, and he discovered it around 1840 in Prague. He preformed the experiment in two segments. In the first experiment, he had a band play music while aboard a moving train, and would have observers listen to the music in a stationary location while the train went by. In the second experiment, he had a group of observers sit aboard a moving train, while the band played in a stationary location. In both cases, observers noticed the phenomenon. The change in sound perception can be explained through relativity.

When the sound source moves toward an observer, each successive wave is emitted closer to the observer than the previous wave. Thus, it will take just a little less time to reach the observer than the previous one. Since the time between waves is reduced, the frequency is increased. Similarly if the sound source is moving away from the observer, the frequency, and therefor pitch, is decreased. If the observer is moving away from the sound source, the frequency will be lowered, and if the observer moves closer to the sound source, the frequency is increased. While the frequency will change whether the observer or sound source is moving, it is easier to show with the sound source as the one moving. This figure demonstrated the sound source moving:

The Doppler Effect: The same sound source is radiating sound waves at a constant frequency in the same medium. However, now the sound source is moving to the right with a speed υs = 0.7 c (Mach 0.7). The wave-fronts are produced with the same frequency as before. However, since the source is moving, the centre of each new wavefront is now slightly displaced to the right. As a result, the wave-fronts begin to bunch up on the right side (in front of) and spread further apart on the left side (behind) of the source.

In classical physics, where the speeds of source and the receiver relative to the medium are lower than the velocity of waves in the medium, the relationship between observed frequency *(f)* and emitted frequency (f_o) is given by: $\mathrm{f}=\frac{(\mathrm{c}+\mathrm{vr})}{(\mathrm{c}+\mathrm{vs})} \times \mathrm{f}_0$ where c – velocity of the sound waves in the medium, v_r– velocity of the observer or reciever, v_s – velocity of the sound source, and f_0 – original frequency of the sound waves.

The above formula assumes that the source is either directly approaching or receding from the observer. If the source approaches the observer at an angle (but still with a constant velocity), the observed frequency that is first heard is higher than the object's emitted frequency. Thereafter, there is a monotonic decrease in the observed frequency as it gets closer to the observer, through equality when it is closest to the observer, and a continued monotonic decrease as it recedes from the observer. When the observer is very close to the path of the object, the transition from high to low frequency is very abrupt. When the observer is far from the path of the object, the transition from high to low frequency is gradual.

If the speeds and are small compared to the speed of the wave, the relationship between observed frequency and emitted frequency is approximately

Observed frequency: $\mathrm{f}=(1+\frac{\Delta \mathrm{v}}{\mathrm{c}})\mathrm{f}_0$

Change in frequency: $\Delta \mathrm{f}=\frac{\Delta \mathrm{v}}{\mathrm{c}}\mathrm{f}_0$

where $\Delta \mathrm{v}$ is the velocity of the receiver relative to the source: it is positive when the source and the receiver are moving towards each other.

Sonic Booms

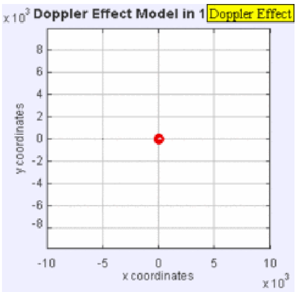
A sonic boom is the sound associated with the shock waves created by an object traveling through the air faster than the speed of sound.

learning objectives

- Identify conditions that lead to a sonic boom and discuss its properties

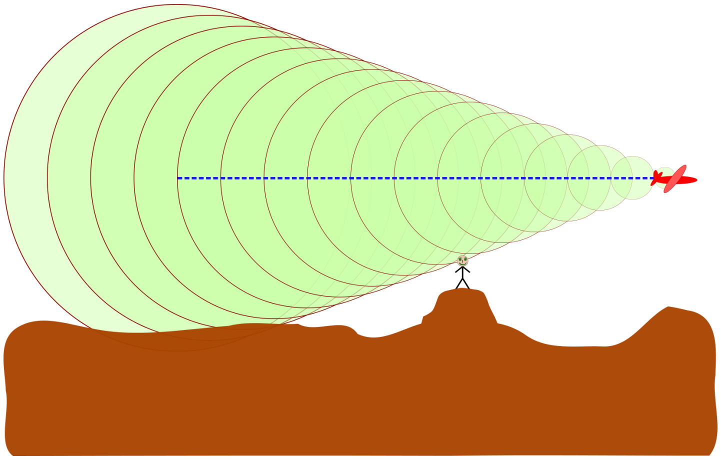
Sonic Booms

A sonic boom is a sound associated with the shock waves created by an object traveling through the air faster than the speed of sound. It can be viewed as a Doppler effect on steroids; sonic booms generate an enormous amount of energy and sound like explosions. The first man-made object to ever create this phenomenon was a bullwhip. The 'crack' of the whip is a result of this sonic boom. This version of a Doppler effect is demonstrated by.



Sonic Boom Gif: The sound source has now broken through the sound speed barrier, and is traveling at 1.4 times the speed of sound, (Mach 1.4). Since the source is moving faster (with a speed) than the sound waves it creates, it actually leads the advancing wavefront. The sound source will pass by a stationary observer (with a speed) before the observer actually hears the sound it creates.

When the sound source passes through the air, it creates a series of pressure waves. These waves are travelling at the speed of sound, and as the speed of the sound source increases, the waves, not being able to get out of each other's way, are forced together. They eventually merge into a single shock wave traveling at the speed of sound. This is a critical speed, known as Mach. The shock waves radiate out from the sound source, and create a "Mach cone'. The half-angle, αα, can be found using the equation



Sonic Boom: A sonic boom produced by an aircraft moving at M=2.92, calculated from the cone angle of 20 degrees. An observer hears the boom when the shock wave, on the edges of the cone, crosses his or her location

$$\sin \alpha = \frac{v_s}{v_r}. \tag{2.3.2}$$

From previous atoms, we know that $\frac{v_s}{v_r}$ is the sound source's Mach number.

At the front of the sound source, there is a sudden rise in pressure, while at the end of the source there is a decreasing pressure. This 'overpressure profile' is known as an N-wave. There is a big boom when there is a sudden change in pressure, and since the pressure changes twice, this is a double boom.

Key Points

- When the object in motion moves towards the other, the frequency is increased because the time between successive sound waves is shortened. Therefore the pitch is higher.
- When the object in motion moves away from the other, the frequency is decreased because the time between successive sound waves is lengthened. Therefor the pitch is lowered.
- Unless the objects are in each other's direct path, you need to account for the angle they are at relative to each other. The following equation needs to be substituted for the 'movers' velocity. The angle used needs to be the angle from the line of sight of the observer to the sound source. vradial=v∗cosθvradial=v∗cosθ.
- When the object in motion moves towards the other, the frequency is increased because the time between successive sound waves is shortened (therefore the pitch is higher).

- When the object in motion moves away from the other, the frequency is decreased because the time between successive sound waves is lengthened (therefore the pitch is lowered).
- Unless the objects are in each other's direct path, you need to account for their angle relative to each other. The following equation must be substituted for the 'movers' velocity. The angle used must be the angle from the line of sight of the observer to the sound source.
- When the object in motion moves towards the other, the frequency is increased because the time between successive sound waves is shortened. Therefore the pitch is higher.
- When the object in motion moves away from the other, the frequency is decreased because the time between successive sound waves is lengthened. Therefor the pitch is lowered.
- If the speeds and are small compared to the speed of the wave, the relationship between observed frequency and emitted frequency is approximately: $f = (1 + \frac{\Delta v}{c}) f_0$ where Δv is the velocity of the receiver relative to the source: it is positive when the source and the receiver are moving towards each other.
- A sonic boom happens when a sound source passes an observer at a speed either very close to, or faster than the speed of sound.
- Sonic booms generate an enormous amount of energy, and sound like explosions.
- The half angle of the cone of sound waves produced by the sonic boom can be found by taking the inverse sine of the object's Mach number.

Key Terms

- **Doppler's effect**: Apparent change in frequency of a wave when the observer and the source of the wave move relative to each other.
- **classical physics**: All aspects of physics developed before the rise of quantum mechanics.
- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: $f = n/t$.
- **Mach number**: The ratio of the velocity of a body to that of sound in the surrounding medium.
- **sonic boom**: The audible effect of a shock wave in the air, especially one caused by an aircraft flying faster than the speed of sound

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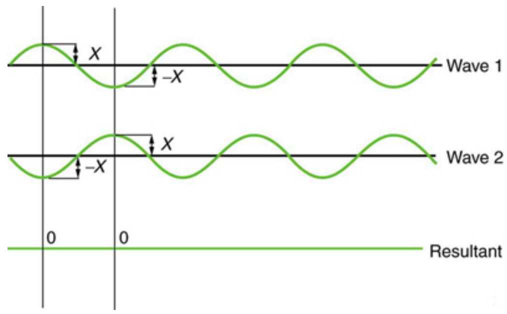
2.4: Interactions with Sound Waves

learning objectives

- Identify conditions required for the superposition of two waves

Waves are most commonly described by variations in some parameter through space and time—height in a water wave, pressure in a sound wave, or the electromagnetic field in a light wave. The value of this parameter is called the amplitude of the wave; the wave itself is a function specifying the amplitude at each point.

When two or more waves arrive at the same point, they superimpose themselves onto one another. More specifically, the disturbances of waves are superimposed when they come together (a phenomenon called superposition). Each disturbance corresponds to a force, or amplitude (and the forces add). If the disturbances are along the same line, the resulting wave is a simple addition of the disturbances of the individual waves. That is, their amplitudes add.

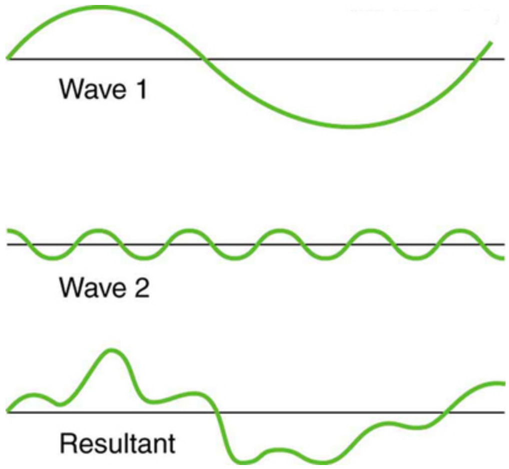


Superposition: Superposition is when two waves add together. In this figure, the two waves add together and cancel out leaving no wave. This is destructive interference.

Superposition of waves leads to what is known as interference, which manifests in two types: constructive and destructive. Constructive interference occurs when two waves add together in superposition, creating a wave with cumulatively higher amplitude, as shown in. In destructive interference, the two waves add together but cancel out (like adding a positive and negative number). Destructive interference is shown in.

While pure constructive and pure destructive interference do occur, they require precisely aligned identical waves. The superposition of most waves produces a combination of constructive and destructive interference, and can vary from place to place and time to time. Sound from a stereo, for example, can be loud in one spot but quiet in another. Varying loudness means the sound waves add partially constructively and partially destructively at different locations. A stereo has at least two speakers creating sound waves, and waves can reflect from walls. All these waves superimpose. An example of sounds that vary over time from constructive to destructive is found in the combined whine of airplane jets heard by a stationary passenger. The combined sound can fluctuate up and down in volume as the sound from the two engines varies in time from constructive to destructive.

These examples are of waves that are similar. illustrates that when non-identical waves superimpose, the outcome is a mixture of constructive and destructive interference.



Superposition of Non-Identical Waves: Superposition of non-identical waves exhibits both constructive and destructive interference.

Interference

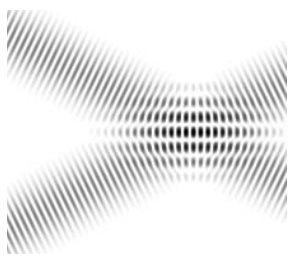
Interference occurs when multiple waves interact with each other, and is a change in amplitude caused by several waves meeting.

learning objectives

- Contrast constructive and destructive interference

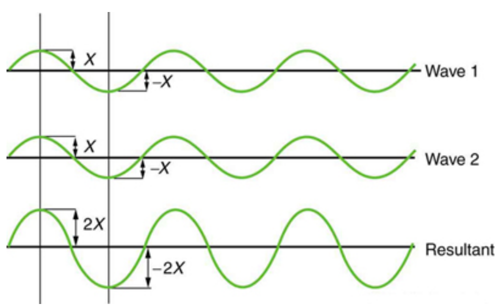
Unlike solid objects, two waves can share a point in space. In physics, interference is a phenomenon in which two waves (passing through the same point) superimpose to form a resultant wave of greater or lower amplitude. Interference usually refers to the interaction of waves that are correlated or coherent with each other (i.e, "interfere" with each other), either because they come from the same source or because they have the same or nearly the same frequency.

The effects of interference can be observed with all types of waves, for example, light, radio, acoustic and surface water waves. The idea that interference is caused by superposition means that when two waves meet their two amplitudes (their maximum absolute value) combine together.



Interference: Two overlapping waves exhibit interference.

Interference can be constructive or destructive. In constructive interference, the two amplitudes of the waves add together and result in a higher displacement than would have been the case if there were only one wave. An example of constructive interference may be seen in.



Constructive Interference: Pure constructive interference of two identical waves produces one with twice the amplitude, but the same wavelength.

Destructive interference is when two waves add together and the result is a smaller displacement than would have been the case. An example of destructive interference can be seen in. When the waves have opposite amplitudes at the point they meet they can destructively interfere, resulting in no amplitude at that point. For example, this is how noise cancelling headphones work. By playing a sound with the opposite amplitude as the incoming sound, the two sound waves destructively interfere and this cancel each other out.

Beats

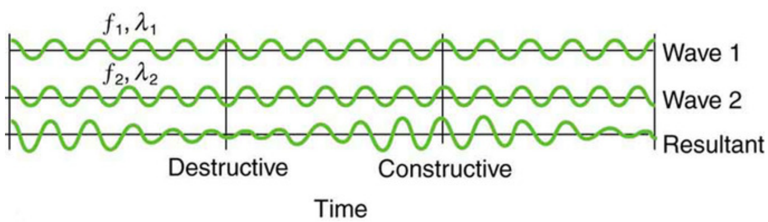
The superposition of two waves of similar but not identical frequencies produces a pulsing known as a beat.

learning objectives

- Identify superposition conditions that lead to beat

Striking two adjacent keys on a piano produces a warbling combination (usually considered unpleasant to the ear). The culprit is the superposition of two waves of similar but not identical frequencies. When two waves of similar frequency arrive at the same point and superimpose, they alternately constructively and destructively interfere. This alternating is known as a beat because it produces an unpleasant pulsing sound.

Another example is often noticeable in a taxiing jet aircraft (particularly the two-engine variety). The loudness of the combined sound of the engines increases and decreases. This varying loudness occurs because the sound waves have similar but not identical frequencies. The discordant warbling of the piano and the fluctuating loudness of the jet engine noise are both due to alternately constructive and destructive interference as the two waves go in and out of phase. illustrates this phenomenon graphically.



Beat Frequency: Beats are produced by the superposition of two waves of slightly different frequencies but identical amplitudes.The waves alternate in time between constructive interference and destructive interference, giving the resulting wave a time-varying amplitude.

The wave resulting from the superposition of two similar-frequency waves has a frequency that is the average of the two. This wave fluctuates in amplitude, or beats, with a frequency called the beat frequency. We can determine the beat frequency mathematically by adding two waves together.

One can also measure the beat frequency directly. When you hear a beat coming from two discordant sounds (say, two notes on a piano) you can count the number of beats per second. The number of beats per second, or the beat frequency, shows the difference in frequency between the two notes. Musicians often use this phenomena to ensure that two notes are in tune (if they are in tune then there are no beats).

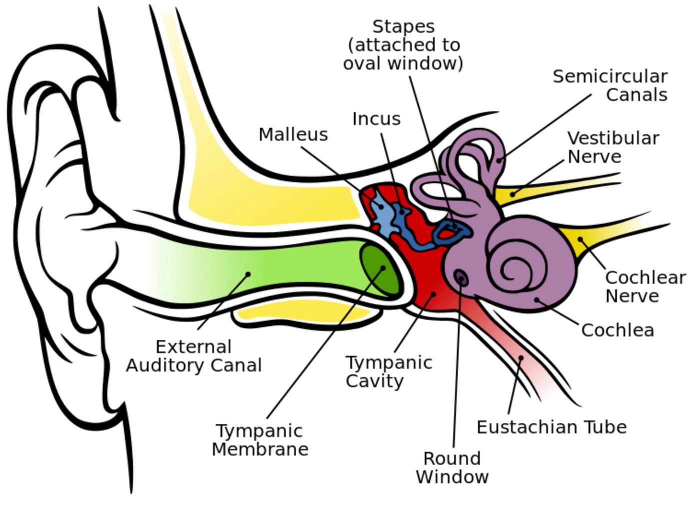
The Ear

The ear is the sensory organ that picks up sound waves from the air and turns them into nerve impulses that can be sent to the brain.

learning objectives

- Describe how sound waves are collected and transformed into nerve impulses

Sound waves are vibrations in the air. The ear is the sensory organ that picks up sound waves from the surrounding air and turns them into nerve impulses, which are then sent to the brain. The sound waves carry a lot of information — language, music, and noise — all mixed together. The task of the ear is to turn the signals in these waves of bouncing air molecules into electrical nerve signals while keeping as much of the information in the signal as possible. (It's the brain's job to then sort the signals and make sense of them.) It’s not easy to turn one kind of signal into another without losing information, but the ear is well designed for the task.



Anatomy of the Human Ear: Anatomy of the human ear; the length of the auditory canal is exaggerated for viewing purposes

Air surrounds the head and fills the ear canal and middle ear. Therefore, when the outer part of the ear collects sound and the middle ear amplifies this sound pressure, these processes occur in the medium of air. However, the hollow channels of the inner ear (which is embedded in the temporal bone, the densest bone of the body) are filled with liquid. So as the sound travels into the inner ear, it passes from the medium of air into a liquid medium. These inner-ear channels contain a sensory epithelium that is studded with hair cells. The microscopic “hairs” are structural protein filaments that project out into the fluid. The hair cells release a chemical neurotransmitter when stimulated. Sound waves moving through fluid push the filaments; if the filaments bend over enough, the hair cells fire chemical signals. In this way sound waves are transformed into nerve impulses. The nerve impulses travel from the left and right ears through the eighth cranial nerve to both sides of the brain stem and up to the part of the cerebral cortex dedicated to sound (auditory cortex, located in the temporal lobe).

Applications: Ultrasound, Sonar, and Medical Imaging

Sound waves reflect off different materials differently (when the reflections are collected, they can provide information and images).

learning objectives

- Discuss application of sound waves in medicine and navigation

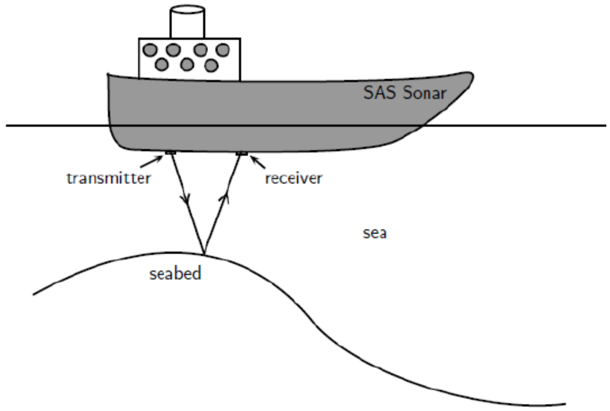
The controlled use of sound waves has many applications in science. Controlled reflection of such waves allows images to be received.

Ultrasound

Ultrasound is sound with a frequency higher than 20 kHz. This is above the human range of hearing. The most common use of ultrasound, creating images, has industrial and medical applications. The use of ultrasound to create images is based on the reflection and transmission of a wave at a boundary. When an ultrasound wave travels inside an object that is made up of different materials (such as the human body), each time it encounters a boundary (e.g., between bone and muscle, or muscle and fat), part of the wave is reflected and part of it is transmitted. The reflected rays are detected and used to construct an image of the object.

Sonar

illustrates how a ship on the ocean utilizes the reflecting properties of sound waves to determine the depth of the ocean. A sound wave is transmitted and bounces off the seabed. Because the speed of sound is known and the time lapse between sending and receiving the sound can be measured, the distance from the ship to the bottom of the ocean can be determined. This technique is called *sonar* (originally an acronym for SOund Navigation And Ranging).



Sonar: Ships on the ocean make use of the reflecting properties of sound waves to determine the depth of the ocean. A sound wave is transmitted and bounces off the seabed. Because the speed of sound is known and the time lapse between sending and receiving the sound can be measured, the distance from the ship to the bottom of the ocean can be determined.

Just as ships on the ocean, certain animals, like dolphins and bats, make use of sounds waves (sonar) to navigate or find their way. Ultrasound waves are sent out then reflected off the objects around the animal. Bats or dolphins then use the reflected sounds to form a “picture” of their surroundings (this is known as echolocation).

Key Points

- When two waves occupy the same point, superposition occurs. Superposition results in adding the two waves together.
- Constructive interference is when two waves superimpose and the resulting wave has a higher amplitude than the previous waves.
- Destructive interference is when two waves superimpose and cancel each other out, leading to a lower amplitude.
- Most wave superpositions involve a mixture of constructive and destructive interference since the waves are not perfectly identical.
- Interference is a phenomenon of wave interactions. When two waves meet at a point, they interfere with each other.
- There are two types of interference, constructive and destructive.
- In constructive interference, the amplitudes of the two waves add together resulting in a higher wave at the point they meet.
- In destructive interference, the two waves cancel out resulting in a lower amplitude at the point they meet.
- When two waves of similar frequencies interfere, the result is a beat frequency.
- A beat frequency is a pulsing sound that goes up and down in loudness.
- As the two waves go in and out of phase, the varying constructive and destructive interference makes the wave grow and shrink in amplitude. For sound waves this produces a beating sound.
- The task of the ear is to turn the signals in the waves of bouncing air molecules into electrical nerve signals while keeping as much of the information in the signals as possible.
- Sound is collected in the outer part of the ear; sound pressure is amplified through the middle part of the ear and is passed from the medium of air into a liquid medium.
- That sound pressure is amplified through the middle portion of the ear and passed from the medium of air into a liquid medium.
- Sound waves moving through the fluid in the inner ear stimulate hair cells, making them release chemical neurotransmitters. In this way sound waves are transformed into nerve impulses.
- When waves encounter a boundary between two materials, part of the wave is reflected and part is transmitted.
- By using high frequency sound waves, doctors can create images of parts of the body normally not visible.
- By transmitting sound waves and measuring the time between the transmission and receiving the reflection, ships can use sound waves to navigate. This is called sonar.

Key Terms

- **superimpose**: To place an object over another object.
- **displacement**: A vector quantity that denotes distance with a directional component.
- **amplitude**: The maximum absolute value of some quantity that varies.
- **coherent**: Of waves having the same direction, wavelength and phase, as light in a laser.

- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time tt in which it occurs: \(\mathrm{f=n/t\).
- **interfere**: (of waves) To be correlated with each other when overlapped or superposed.
- **superposition**: The summing of two or more field contributions occupying the same space.
- **epithelium**: a membranous tissue composed of one or more layers of cells that forms the covering of most internal and external surfaces of the body and its organs (internally, the lining of vessels and other small cavities; externally, the skin)
- **nerve impulse**: the signal transmitted along a nerve fiber, either in response to a stimulus (such as touch, pain, or heat), or as an instruction (such as causing a muscle to contract)
- **neurotransmitter**: any substance, such as acetylcholine or dopamine, responsible for sending nerve signals across a synapse between two neurons

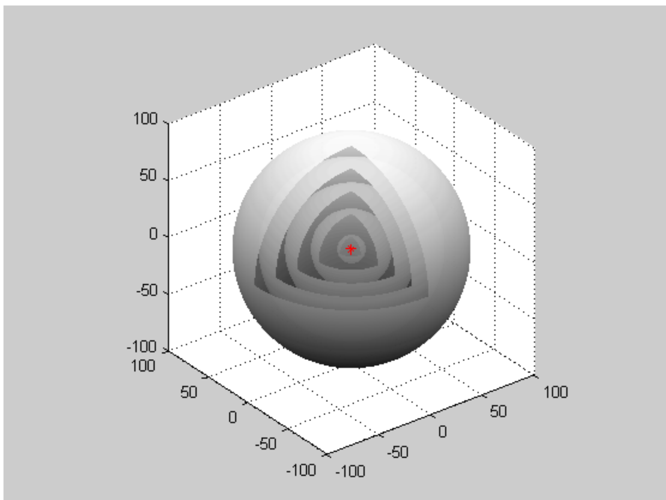
2.5: Further Topics

learning objectives

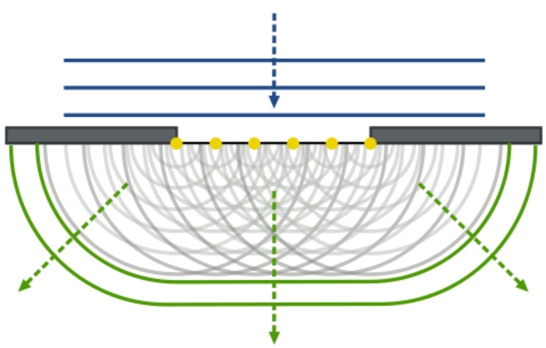
- Identify sources of spherical and plane wave patterns

Spherical Waves

Christiaan Huygens was a Dutch scientist who developed a useful technique for determining how and where waves propagate. In 1678, he proposed that every point that a luminous disturbance touches becomes itself a source of a spherical wave; the sum of these secondary waves determines the form of the wave at any subsequent time. The Huygen-Fresnel Principle shows that as the waves interact with each other, they interfere either constructively or destructively. Constructive interference occurs when waves are completely in phase with each other and amplifies the waves. Destructive interference occurs when waves are exactly out of phase with either other, and if waves are perfectly out of phase with each other, the wave will be canceled out completely. Since the waves all come from one point source, the waves happen in a spherical pattern. All the waves come from a single point source and are spherical.



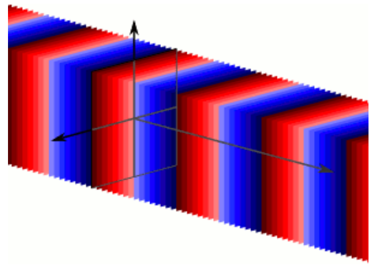
***Spherical Wave**: When waves are produced from a point source, they are spherical waves.*



Huygen-Fresnel Principle: The Huygen-Fresnel Principle uses the law of refraction. Each point on the wave produces waves which interfere with each other either constructively or destructively.

Plane Waves

A plane wave is a constant-frequency wave whose wavefronts (surfaces of constant phase) are infinite parallel planes of constant peak-to-peak amplitude normal to the phase velocity vector. It is not possible in practice to have a true plane wave; only a plane wave of infinite extent will propagate as a plane wave. However, many waves are approximately plane waves in a localized region of space. For example, a localized source such as an antenna produces a field that is approximately a plane wave far from the antenna in its far-field region. Similarly, if the length scales are much longer than the wave's wavelength, as is often the case for light in the field of optics, one can treat the waves as light rays which correspond locally to plane waves.



***Plane Wave**: Plane waves are an infinite number of wavefronts normal to the direction of the propogation.*

Standing Waves on a String

Standing wave occurs due to the interference when transverse waves in strings are reflected and the incident and reflected waves meet.

learning objectives

- Identify when a standing wave occurs

A standing wave is a wave that appears stationary, meaning it remains in a constant position. In a string, a standing wave is a type of transverse wave—where the movement of the particles of the medium is perpendicular to the direction of the propagation of the wave. A standing wave can occur when two identical waves moving in different directions along the string interfere.

There are two scenarios of waves in strings: the string is fixed at both ends, or the string is fixed at one end and free at the other. A transverse wave will move along the string until it reaches the other end. It is then reflected from that end and starts to move back towards the original direction; at this point interference occurs. shows a transverse wave that is reflected from a fixed end. When a transverse wave meets a fixed end, the wave is reflected, but inverted. This swaps the peaks with the troughs and the troughs with the peaks. diagrams a transverse wave on a string that meets a free end. The wave is reflected, but unlike a transverse wave with a fixed end, it is not inverted.

Free End Reflection: The wave is reflected, but unlike a transverse wave with a fixed end, it is not inverted.

Fixed End Reflection: When a transverse wave meets a fixed end, the wave is reflected, but inverted.

Standing Waves

When either of the two scenarios of wave reflection occurs, the incident wave meets the reflected wave. These waves move past each other in opposite directions, causing interference. When these two waves have the same frequency, the product of this is called the standing waves. Standing waves appear to be standing still, hence the name. illustrates a very slow moving standing wave. (One application of the principle of standing waves is in music with the concept of resonance—and how many musical instruments, like guitars and pianos, get their sound.) Let us now examine how standing waves occur.

Standing Wave on a String: This is what a standing wave would look like if you were to slow it down. The wave is caused by an incident wave on a string being reflected and then traveling back in the direction it came from. The two waves then meet and interfere with each other causing this phenomenon.

Constructive vs. Destructive Interference

When the incident wave and reflected wave first meet, both waves have an amplitude is zero. As the waves continue to move past each other they continue to interfere with each other, either constructively of destructively. As discussed in previous atoms, when waves are completely in phase and interfere with each other constructively they are amplified, and when they are completely out of phase and interfere destructively they cancel out. As the waves continue to move past each other, and are reflected from the opposite end, they continue to interfere both ways; a standing wave is produced. Every point in the medium containing a standing wave oscillates up and down, and the amplitude of the oscillations depends on the location of the point. When we observe a standing wave on strings, it appears the wave is not moving but standing still. In summary:

- The points which reach the maximum oscillation height are called antinodes, and are results of complete constructive interference.
- The points in a standing wave that appear to remain flat and do not move are called nodes. These are due to complete destructive interference.

Standing Waves in Air Columns

Standing waves in air columns is the physical phenomenon that gives wind instruments their resonance and, therefore, sound.

learning objectives

- Identify the type of a standing wave in an air column

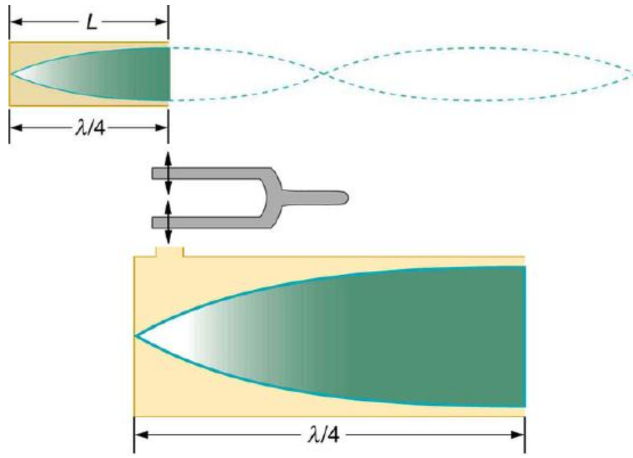
Standing Waves

A standing wave is a wave that appears to be stationary, meaning it remains in a constant position. In an air column, a standing wave can form as either a longitudinal or transverse wave. A transverse wave, you may remember, is a wave where the movement of the particles of the medium is perpendicular to the direction of the propagation of the wave. A longitudinal wave, on the other hand, is parallel to the direction of propagation. A standing wave can occur when two identical waves moving in different directions interfere.

Air Columns

When a standing wave is formed in a tube, the standing wave has a maximum air displacement at the open end called an antinode. Here, the motion is unconstrained. At the closed end, there is no displacement; this is called a node, and the air is halted. The distance from a node to antinode is 1/4 of a wavelength, and is equal to the length of the tube.

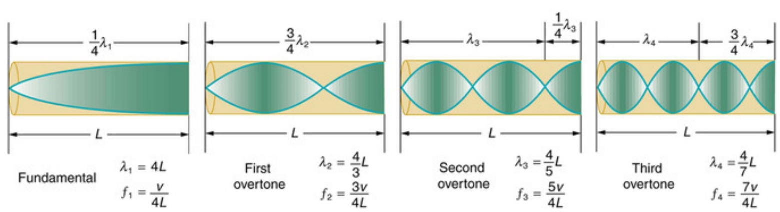
shows that this resonance can be produced by a vibration introduced at or near the closed end of the tube as well. This is considered to be a natural vibration of the air column independently of how it is induced. Given that maximum air displacements are possible at the open end and none at the closed end, there are other, shorter wavelengths that can resonate in the tube. For example, a standing wave can have three-fourths of its wavelength in the tube, or $L=(3/4)\lambda$. This can be rendered as follows:



Standing Wave in Air Column: The same standing wave is created in the tube by a vibration introduced near its closed end.

$$\lambda' = \frac{4L}{3} \tag{2.5.1}$$

Continuing this process reveals a whole series of shorter-wavelength and higher-frequency sounds that resonate in the tube. We use specific terms for the resonances in any system. The lowest resonant frequency is called the fundamental, while all higher resonant frequencies are called overtones. All resonant frequencies are integral multiples of the fundamental, and they are collectively called harmonics. The fundamental is the first harmonic, the first overtone is the second harmonic, and so on. shows hows the fundamental and the first three overtones (the first four harmonics) in a tube closed at one end.



The First Four Harmonics: The fundamental and three lowest overtones for a tube closed at one end. All have maximum air displacements at the open end and none at the closed end.

Now let us look for a pattern in the resonant frequencies for a simple tube that is closed at one end. The fundamental has =4L, and frequency is related to wavelength and the speed of sound as given by the following:

$$\mathbf{v}_{\mathrm{w}} = \mathrm{f}\lambda \tag{2.5.2}$$

Solving for f in this equation gives a more helpful form:

$$\mathrm{f} = \frac{\mathrm{v_w}}{\lambda} = \frac{\mathbf{v}_{\mathrm{w}}}{4\mathrm{L}} \tag{2.5.3}$$

Here, f is frequency, v_w is speed of sound in air, λ is wavelength, and L is the length of the air column. The first overtone has = 4L/3. From this, we can deduce the following:

$$\mathrm{f}' = 3\frac{v_{\mathrm{w}}}{4\mathrm{L}} = 3\mathrm{f} \tag{2.5.4}$$

Because f′ = 3f, we call the first overtone the third harmonic. Continuing this process, we see a pattern that can be generalized in a single expression. The resonant frequencies of a tube closed at one end are:

$$\mathrm{f_n} = \mathrm{n}\frac{\mathrm{vw}}{4\mathrm{L}}, \mathrm{n} = 1, 3, 5 \tag{2.5.5}$$

Here, f1 is the fundamental, f3 is the first overtone, and so on. It is interesting that the resonant frequencies depend on the speed of sound and, hence, on temperature. This dependence poses a noticeable problem for organs in old unheated cathedrals, and it is also the reason why musicians commonly bring their wind instruments to room temperature before playing them.

Example 2.5.1:

The fundamental and overtones can be present simultaneously in a variety of combinations. For example, middle C on a trumpet has a sound distinctively different from middle C on a clarinet, both instruments being modified versions of a tube closed at one end. The fundamental frequency is the same (and usually the most intense), but the overtones and their mix of intensities are different and subject to shading by the musician. This mix is what gives various musical instruments (and human voices) their distinctive characteristics, whether they have air columns, strings, sounding boxes, or drumheads. In fact, much of our speech is determined by shaping the cavity formed by the throat and mouth and positioning the tongue to adjust the fundamental and combination of overtones. Simple resonant cavities can be made to resonate with the sound of the vowels, for example.

Forced Vibrations and Resonance

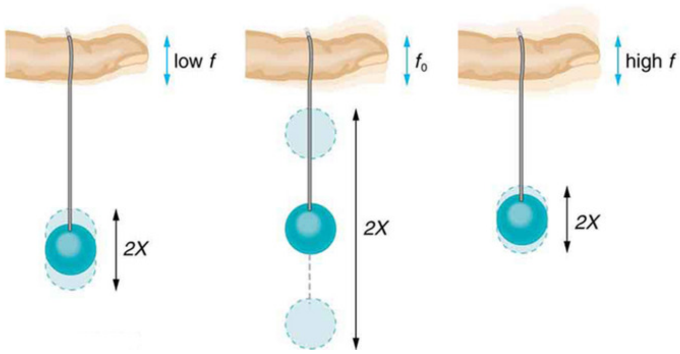
The phenomenon of driving a system with a frequency equal to its natural frequency is called resonance.

learning objectives

- Explain the relationship between the resonance curve and damping

Forced Vibration and Resonance

Many people have played with toys involving an object supported by an elastic band: something like the paddle ball suspended from a finger in. Say a person drives the paddle ball by moving his or her finger up and down at a certain frequency. In this example, he or she is causing a forced oscillation (or vibration). At first the finger is held steady, and the ball bounces up and down with a small amount of damping. If the finger is moved up and down slowly, the ball will follow along without bouncing much on its own.

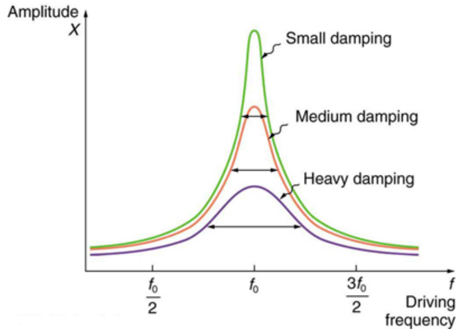


Paddle Balls and Frequencies: The paddle ball on its rubber band moves in response to the finger supporting it. If the finger moves with the natural frequency f0 of the ball on the rubber band, then a resonance is achieved, and the amplitude of the ball's oscillations increases dramatically. At higher and lower driving frequencies, energy is transferred to the ball less efficiently, and it responds with lower-amplitude oscillations.

As the frequency at which the finger is moved up and down increases, the ball will respond by oscillating with increasing amplitude. After driving the ball at its natural frequency, the ball's oscillations increase in amplitude with each oscillation for as long as it is driven. The phenomenon of driving a system with a frequency equal to its natural frequency is called resonance. As the driving frequency gets progressively higher than the resonant or natural frequency, the amplitude of the oscillations becomes smaller until the oscillations nearly disappear and the finger simply moves up and down with little effect on the ball.

Effects of Damping

In real life, most oscillators have damping present in the system. It is interesting that the widths of the resonance curves shown in depend on damping: the less the damping, the narrower the resonance. For a driven oscillator to resonate at a very specific frequency, there needs to be as little damping as possible, as is the case for piano strings and many other musical instruments. Conversely, for small-amplitude oscillations, such as in a car's suspension system, there needs to be heavy damping. Heavy damping reduces the amplitude, but the tradeoff is that the system responds at more frequencies.



Damping: The amplitude of a harmonic oscillator is a function of the frequency of the driving force. The curves represent the same oscillator with the same natural frequency but with different amounts of damping. Resonance occurs when the driving frequency equals the natural frequency, and the greatest response is for the least amount of damping. The narrowest response is also for the least amount of damping.

Example 2.5.2:

These features of driven harmonic oscillators apply to a huge variety of systems. When tuning a radio, for example, people are adjusting the resonant frequency of the radio circuit so that it only oscillates to the desired station's broadcast (or driving) frequency. The more selective the radio is in discriminating between stations, the smaller its damping. A child on a swing is driven by a parent at the swing's natural frequency to achieve maximum amplitude. In all of these cases, the efficiency of energy transfer from the driving force into the oscillator is best at resonance. On gravel roads that are corrugated, if people travel at the 'wrong' speed, the bumps are very noticeable. At other speeds, it is difficult to feel the bumps at all. shows a photograph of a famous example (the Tacoma Narrows Bridge) of the destructive effects of a driven harmonic oscillation. Unfortunately, heavy winds happened to drive the bridge at its natural frequency, leading to the collapse.

Collapse of the Tacoma Narrows Bridge: In 1940, the Tacoma Narrows Bridge in Washington state collapsed. Heavy cross winds drove the bridge into oscillations at its resonant frequency. The damping decreased when support cables broke loose and started to slip over the towers, allowing increasingly greater amplitudes until the structure failed. (credit: PRI's Studio 360, via Flickr)

Key Points

- The waves either interfere with each other constructively or destructively, which will either amplify or minimize the wave, respectively.
- Spherical waves are emitted from a single point source in a spherical shape.
- A plane wave is a constant-frequency wave whose wavefronts (surfaces of constant phase) are infinite parallel planes of constant peak-to-peak amplitude normal to the phase velocity vector.
- Although it is not possible in practice to have a true plane wave, many waves approximate plane wave behavior.
- The reflected wave is inverted from the incident wave when a transverse wave on a string is fixed at the end point. The reflected wave is not inverted from the incident wave when a transverse wave on a string is free at the end point.
- A standing wave occurs when an incident wave meets a reflected wave on a string.
- A standing wave contains nodes (points that remain flat due to the destructive interference) and antinodes (points with maximum oscillation due to the constructive interference).

- Every point in the string oscillates up and down and the amplitude of the oscillations depends on the location of the point.
- A standing wave has some points that remain flat due to destructive interference. These are called antinodes.
- The points on a standing wave that have reached maximum oscillation do so from constructive interference, and are called nodes.
- A standing wave in an air column is a transverse wave.
- A node occurs at the closed end of an air tube where there is no wave displacement.
- An antinode occurs at the open end of the air tube where the maximum displacement occurs.
- The resonant frequencies of a tube closed at one end are as follows: $f_n = n\frac{vw}{4L}$, n=1,3,5.
- Any oscillator has a natural frequency. Driven at the natural frequency, oscillations increase in amplitude with each oscillation.
- The widths of the resonance curves depend on damping: less damping corresponds to a narrower resonance. With less damping, the resonance peak becomes more pronounced.
- The relationship between resonance and damping applies to a huge variety of systems. Damping is often reduced or enhanced to induce the desired response of an oscillator.

Key Terms

- **wavefront**: An imaginary surface passing through points of a medium oscillating in phase.
- **destructive interference**: Occurs when waves interfere with each other crest to trough (peak to valley) and are exactly out of phase with each other.
- **constructive interference**: Occurs when waves interfere with each other crest to crest and the waves are exactly in phase with each other.
- **transverse wave**: Any wave in which the direction of disturbance is perpendicular to the direction of travel.
- **natural frequency**: The frequency at which a system vibrates on its own. For a spring (spring constant k) with an object of mass m attached, the natural frequency is given as $f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$.
- **damping**: The reduction in the magnitude of oscillations by the dissipation of energy

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CHAPTER OVERVIEW

3: Electromagnetic Waves

Topic hierarchy

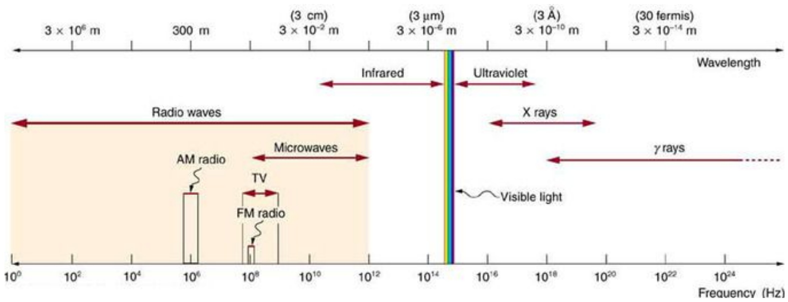
3.1: The Electromagnetic Spectrum

learning objectives

- Compare properties of AM and FM radio waves

Radio Waves

Radio waves are a type of electromagnetic (EM) radiation with wavelengths in the electromagnetic spectrum longer than infrared light. They have have frequencies from 300 GHz to as low as 3 kHz, and corresponding wavelengths from 1 millimeter to 100 kilometers. Like all other electromagnetic waves, radio waves travel at the speed of light. Naturally occurring radio waves are made by lightning or by astronomical objects. Artificially generated radio waves are used for fixed and mobile radio communication, broadcasting, radar and other navigation systems, communications satellites, computer networks and innumerable other applications. Different frequencies of radio waves have different propagation characteristics in the Earth's atmosphere—long waves may cover a part of the Earth very consistently, shorter waves can reflect off the ionosphere and travel around the world, and much shorter wavelengths bend or reflect very little and travel on a line of sight.



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves encompass the high frequency portion of the radio section of the EM spectrum.

Types of Radio Waves and Applications

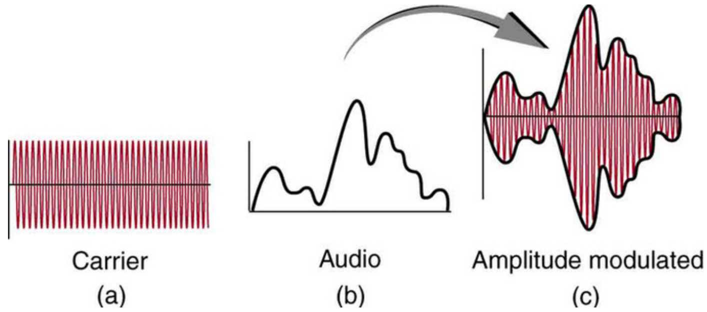
Radio waves have many uses—the category is divided into many subcategories, including microwaves and electromagnetic waves used for AM and FM radio, cellular telephones and TV.

The lowest commonly encountered radio frequencies are produced by high-voltage AC power transmission lines at frequencies of 50 or 60 Hz. These extremely long wavelength electromagnetic waves (about 6000 km) are one means of energy loss in long-distance power transmission.

Extremely low frequency (ELF) radio waves of about 1 kHz are used to communicate with submerged submarines. The ability of radio waves to penetrate salt water is related to their wavelength (much like ultrasound penetrating tissue)—the longer the wavelength, the farther they penetrate. Since salt water is a good conductor, radio waves are strongly absorbed by it; very long wavelengths are needed to reach a submarine under the surface.

AM Radio Waves

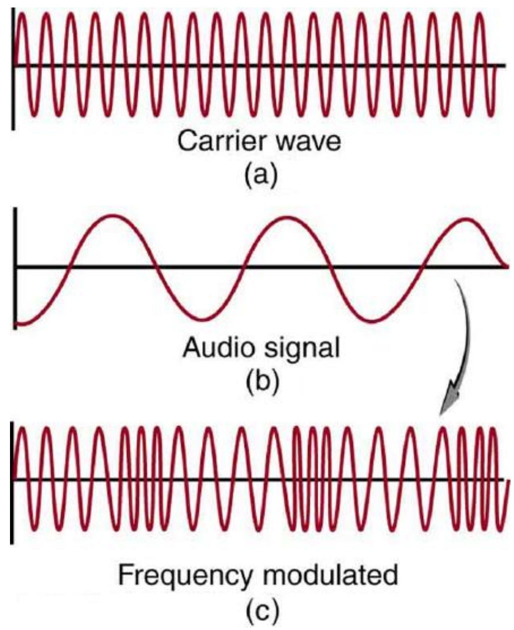
AM radio waves are used to carry commercial radio signals in the frequency range from 540 to 1600 kHz. The abbreviation AM stands for amplitude modulation—the method for placing information on these waves. A carrier wave having the basic frequency of the radio station (for instance, 1530 kHz) is varied or modulated in amplitude by an audio signal. The resulting wave has a constant frequency, but a varying amplitude.



AM Radio: Amplitude modulation for AM radio. (a) A carrier wave at the station's basic frequency. (b) An audio signal at much lower audible frequencies. (c) The amplitude of the carrier is modulated by the audio signal without changing its basic frequency.

FM Radio Waves

FM radio waves are also used for commercial radio transmission, but in the frequency range of 88 to 108 MHz. FM stands for frequency modulation, another method of carrying information. In this case, a carrier wave having the basic frequency of the radio station (perhaps 105.1 MHz) is modulated in frequency by the audio signal, producing a wave of constant amplitude but varying frequency.



FM Radio: Frequency modulation for FM radio. (a) A carrier wave at the station's basic frequency. (b) An audio signal at much lower audible frequencies. (c) The frequency of the carrier is modulated by the audio signal without changing its amplitude.

Since audible frequencies range up to 20 kHz (or 0.020 MHz) at most, the frequency of the FM radio wave can vary from the carrier by as much as 0.020 MHz. For this reason, the carrier frequencies of two different radio stations cannot be closer than 0.020 MHz. An FM receiver is tuned to resonate at the carrier frequency and has circuitry that responds to variations in frequency, reproducing the audio information.

FM radio is inherently less subject to noise from stray radio sources than AM radio because amplitudes of waves add noise. Thus, an AM receiver would interpret noise added onto the amplitude of its carrier wave as part of the information. An FM receiver can be fashioned to reject amplitudes other than that of the basic carrier wave and only look for variations in frequency. Thus, since noise produces a variation in amplitude, it is easier to reject noise from FM.

TV

Electromagnetic waves also broadcast television transmission. However, as the waves must carry a great deal of visual as well as audio information, each channel requires a larger range of frequencies than simple radio transmission. TV channels utilize frequencies in the range of 54 to 88 MHz and 174 to 222 MHz (the entire FM radio band lies between channels 88 MHz and 174

MHz). These TV channels are called VHF (very high frequency). Other channels called UHF (ultra high frequency) utilize an even higher frequency range of 470 to 1000 MHz.

The TV video signal is AM, while the TV audio is FM. Note that these frequencies are those of free transmission with the user utilizing an old-fashioned roof antenna. Satellite dishes and cable transmission of TV occurs at significantly higher frequencies, and is rapidly evolving with the use of the high-definition or HD format.

Microwaves

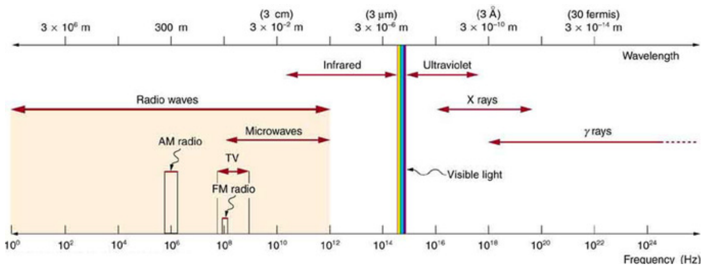
Microwaves are electromagnetic waves with wavelengths ranging from one meter to one millimeter (frequencies between 300 MHz and 300 GHz).

Learning objectives

- Distinguish three ranges of the microwave portion of the electromagnetic spectrum

Microwaves

Microwaves are electromagnetic waves with wavelengths ranging from as long as one meter to as short as one millimeter, or equivalently with frequencies between 300 MHz (0.3 GHz) and 300 GHz. The microwave region of the electromagnetic (EM) spectrum is generally considered to overlap with the highest frequency (shortest wavelength) radio waves. As is the case for all EM waves, microwaves travel in a vacuum at the speed of light. The prefix “micro-” in “microwave” is not meant to suggest a wavelength in the micrometer range. It indicates that microwaves are “small” because have shorter wavelengths as compared to waves used in typical radio broadcasting. The boundaries between far infrared light, terahertz radiation, microwaves, and ultra-high-frequency radio waves are fairly arbitrary. They are used variously between different fields of study (see figure).



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves overlap with the high frequency portion of the radio section of the EM spectrum.

Subcategories of Microwaves

The microwave portion of the radio spectrum can be subdivided into three ranges, listed below from high to low frequencies.

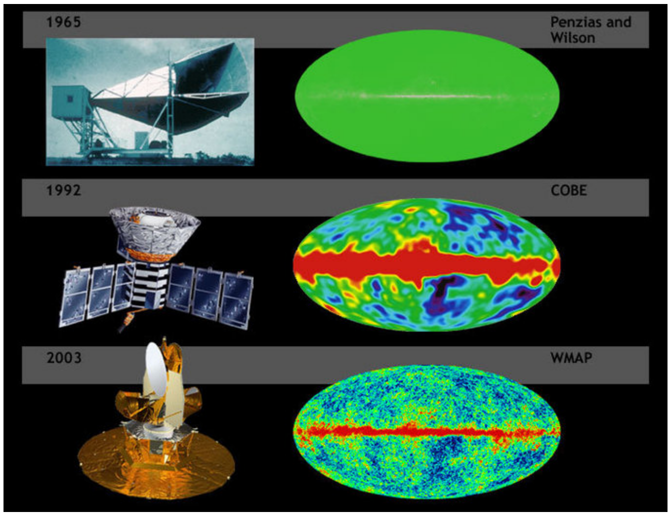
- Extremely high frequency (EHF) is the highest microwave frequency band. EHF runs the range of frequencies from 30 to 300 gigahertz, above which electromagnetic radiation is considered as far infrared light, also referred to as terahertz radiation. This frequency range corresponds to a wavelength range of 10 to 1 millimeter, so it is sometimes called the millimeter band. This band is commonly used in radio astronomy and remote sensing.
- Super high frequency (SHF) is the designation for electromagnetic wave frequencies in the range of 3 GHz to 30 GHz. This band of frequencies is known also as the centimeter band because the wavelengths range from ten to one centimeters. This frequency range is used for most radar transmitters, microwave ovens, wireless LANs, cell phones, satellite communication, microwave radio relay links, and numerous short range terrestrial data links.
- Ultra-high frequency (UHF) designates the microwave frequency range of electromagnetic waves between 300 MHz and 3 GHz, also known as the decimeter band because the wavelengths range from one to ten decimeters, or 10 centimeters to 1 meter. They are used for television broadcasting, cordless phones, walkie-talkies, satellite communication, and numerous other applications.

Sources of Microwaves

Microwaves are the highest-frequency electromagnetic waves that can be produced by currents in macroscopic circuits and devices. Microwaves can also be produced by atoms and molecules—e.g., they are a component of electromagnetic radiation generated by *thermal agitation*. The thermal motion of atoms and molecules in any object at a temperature above absolute zero causes them to emit and absorb radiation.

Since it is possible to carry more information per unit time on high frequencies, microwaves are quite suitable for communications devices. Most satellite-transmitted information is carried on microwaves, as are land-based long-distance transmissions. A clear line of sight between transmitter and receiver is needed because of the short wavelengths involved.

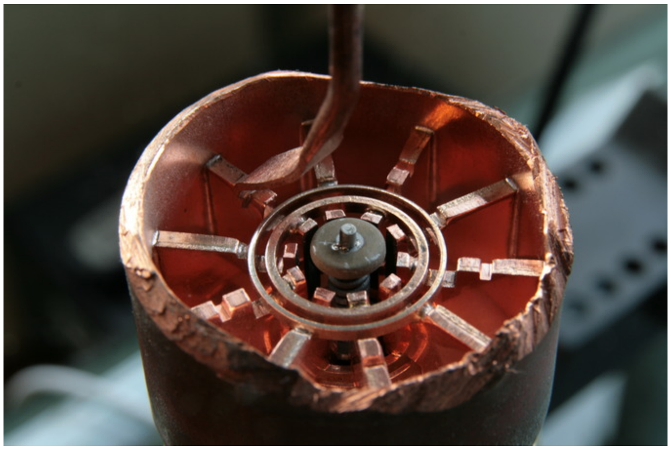
The sun also emits microwave radiation, although most of it is blocked by Earth's atmosphere. The Cosmic Microwave Background Radiation (CMBR) is microwave radiation that permeates all of space, and its discovery supports the Big Bang theory of the origin of the universe.



Cosmic Microwave Background: Cosmic background radiation of the Big Bang mapped with increasing resolution.

Devices Employing Microwaves

High-power microwave sources use specialized vacuum tubes to generate microwaves. These devices operate on different principles from low-frequency vacuum tubes, using the ballistic motion of electrons in a vacuum under the influence of controlling electric or magnetic fields, and include the magnetron (used in microwave ovens), klystron, traveling-wave tube (TWT), and gyrotron.



Cavity Magnetron: Cutaway view inside a cavity magnetron as used in a microwave oven.

Microwaves are used by microwave ovens to heat food. Microwaves at a frequency of 2.45 GHz are produced by accelerating electrons. The microwaves then induce an alternating electric field in the oven. Water and some other constituents of food have a slightly negative charge at one end and a slightly positive charge at one end (called polar molecules). The range of microwave frequencies is specially selected so that the polar molecules, in trying to maintain their orientation with the electric field, absorb these energies and increase their temperatures—a process called *dielectric heating*.

Radar, first developed in World War II, is a common application of microwaves. By detecting and timing microwave echoes, radar systems can determine the distance to objects as diverse as clouds and aircraft. A Doppler shift in the radar echo can determine the speed of a car or the intensity of a rainstorm. Sophisticated radar systems can map the Earth and other planets, with a resolution limited by wavelength. The shorter the wavelength of any probe, the smaller the detail it is possible to observe.

A *maser* is a device similar to a laser, which amplifies light energy by stimulating photons. The maser, rather than amplifying visible light energy, amplifies the lower-frequency, longer-wavelength microwaves and radio frequency emissions.

Infrared Waves

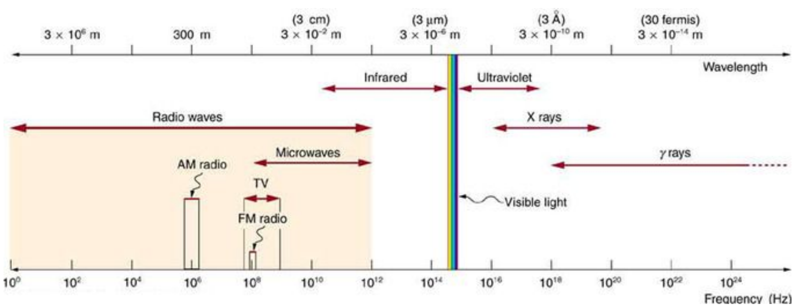
Infrared (IR) light is EM radiation with wavelengths longer than those of visible light from 0.74 µm to 1 mm (300 GHz to 1 THz).

Skills to Develop

- Distinguish three ranges of the infrared portion of the spectrum, and describe processes of absorption and emission of infrared light by molecules

Infrared Waves

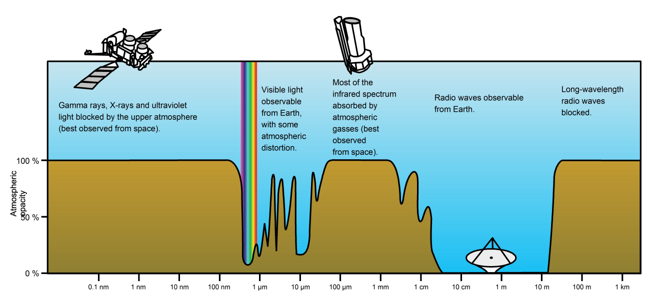
Infrared (IR) light is electromagnetic radiation with longer wavelengths than those of visible light, extending from the nominal red edge of the visible spectrum at 0.74 micrometers (µm) to 1 mm. This range of wavelengths corresponds to a frequency range of approximately 300 GHz to 400 THz, and includes most of the thermal radiation emitted by objects near room temperature. Infrared light is emitted or absorbed by molecules when they change their rotational-vibrational movements.



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves encompass the high frequency portion of the radio section of the EM spectrum.

Subcategories of IR Waves

The infrared part of the electromagnetic spectrum covers the range from roughly 300 GHz (1 mm) to 400 THz (750 nm). It can be divided into three parts: It can be divided into three parts:



Atmospheric Transmittance: This is a plot of Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation. Most UV wavelengths are absorbed by oxygen and ozone in Earth's atmosphere. Observations of astronomical UV sources must be done from space.

- Far-infrared, from 300 GHz (1 mm) to 30 THz (10 μm) – The lower part of this range may also be called microwaves. This radiation is typically absorbed by so-called rotational modes in gas-phase molecules, by molecular motions in liquids, and by phonons in solids. The water in Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere in effect opaque. However, there are certain wavelength ranges ("windows") within the opaque range that allow partial transmission, and can be used for astronomy. The wavelength range from approximately 200 μm up to a few mm is often referred to as "sub-millimeter" in astronomy, reserving far infrared for wavelengths below 200 μm.
- Mid-infrared, from 30 to 120 THz (10 to 2.5 μm) – Hot objects (black-body radiators) can radiate strongly in this range, and human skin at normal body temperature radiates strongly at the lower end of this region. This radiation is absorbed by molecular vibrations, where the different atoms in a molecule vibrate around their equilibrium positions. This range is sometimes called the fingerprint region, since the mid-infrared absorption spectrum of a compound is very specific for that compound.
- Near-infrared, from 120 to 400 THz (2,500 to 750 nm) – Physical processes that are relevant for this range are similar to those for visible light. The highest frequences in this region can be detected directly by some types of photographic film, and by many types of solid state image sensors for infrared photography and videography.

Note that in some fields the boundaries of these categories differ slightly; for example, in astronomy "near-infrared" is considered to extend to 5 μm rather than 2.5 μm.

Heat and Thermal Radiation

Infrared radiation is popularly known as "heat radiation," but light and electromagnetic waves of any frequency will heat surfaces that absorb them. Infrared light from the Sun only accounts for 49% of the heating of the Earth, with the rest being caused by visible light that is absorbed then re-radiated at longer wavelengths. Visible light or ultraviolet-emitting lasers can char paper and incandescently hot objects emit visible radiation. Objects at room temperature will emit radiation mostly concentrated in the 8 to 25 μm band, but this is not distinct from the emission of visible light by incandescent objects and ultraviolet by even hotter objects (see sections on black body radiation and Wien's displacement law).

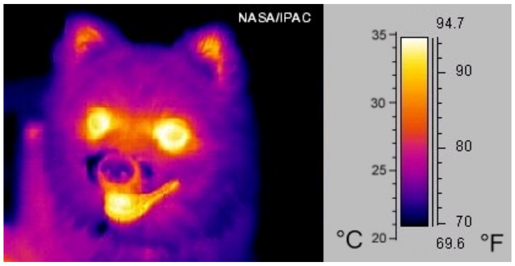
Heat is energy in transient form that flows due to temperature difference. Unlike heat transmitted by thermal conduction or thermal convection, radiation can propagate through a vacuum.

The concept of emissivity is important in understanding the infrared emissions of objects. This is a property of a surface which describes how its thermal emissions deviate from the ideal of a black body. To further explain, two objects at the same physical temperature will not "appear" the same temperature in an infrared image if they have differing emissivities.

Sources of IR Waves

As stated above, while infrared radiation is commonly referred to as heat radiation, only objects emitting with a certain range of temperatures and emissivities will produce most of their electromagnetic emission in the infrared part of the spectrum. However, this is the case for most objects and environments humans encounter in our daily lives. Humans, their surroundings, and the Earth itself emit most of their thermal radiation at wavelengths near 10 microns, the boundary between mid and far infrared according to the delineation above. The range of wavelengths most relevant to thermally emitting objects on earth is often called the thermal infrared. Many astronomical objects emit detectable amounts of IR radiation at non-thermal wavelengths.

Infrared radiation can be used to remotely determine the temperature of objects (if the emissivity is known). This is termed thermography, mainly used in military and industrial applications but the technology is reaching the public market in the form of infrared cameras on cars due to the massively reduced production costs.



Thermography: A thermographic image of a dog

Applications of IR waves extend to heating, communication, meteorology, spectroscopy, astronomy, biological and medical science, and even the analysis of works of art.

Visible Light

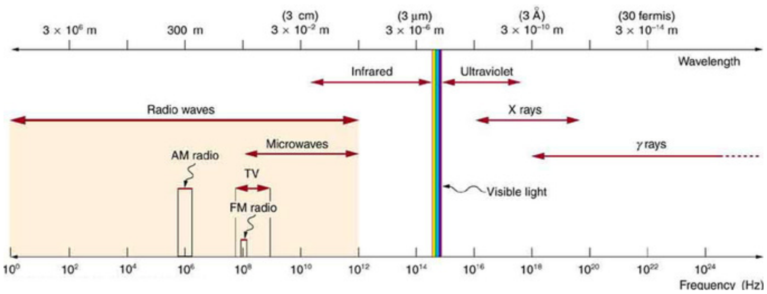
Visible light is the portion of the electromagnetic spectrum that is visible to the human eye, ranging from roughly 390 to 750 nm.

Skills to Develop

- Distinguish six ranges of the visible spectrum

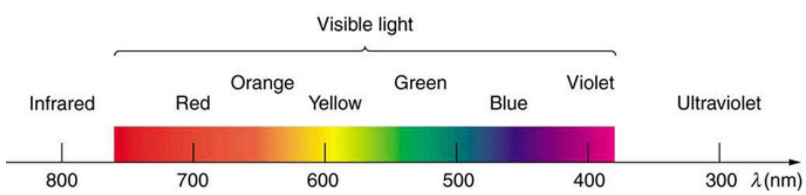
Visible Light

Visible light, as called the visible spectrum, is the portion of the electromagnetic spectrum that is visible to (can be detected by) the human eye. Electromagnetic radiation in this range of wavelengths is often simply referred to as “light”. A typical human eye will respond to wavelengths from about 390 to 750 nm (0.39 to 0.75 µm). In terms of frequency, this corresponds to a band in the vicinity of 400–790 THz. A light-adapted eye generally has its maximum sensitivity at around 555 nm (540 THz), in the green region of the optical spectrum. The spectrum does not, however, contain all the colors that the human eyes and brain can distinguish. Unsaturated colors such as pink, or purple variations such as magenta, are absent, for example, because they can be made only by a mix of multiple wavelengths.



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves encompass the high frequency portion of the radio section of the EM spectrum.

Visible light is produced by vibrations and rotations of atoms and molecules, as well as by electronic transitions within atoms and molecules. The receivers or detectors of light largely utilize electronic transitions. We say the atoms and molecules are excited when they absorb and relax when they emit through electronic transitions.



Visible Spectrum: A small part of the electromagnetic spectrum that includes its visible components. The divisions between infrared, visible, and ultraviolet are not perfectly distinct, nor are those between the seven rainbow colors.

The figure above shows this part of the spectrum, together with the colors associated with particular pure wavelengths. Red light has the lowest frequencies and longest wavelengths, while violet has the highest frequencies and shortest wavelengths. Blackbody radiation from the Sun peaks in the visible part of the spectrum but is more intense in the red than in the violet, making the Sun yellowish in appearance.

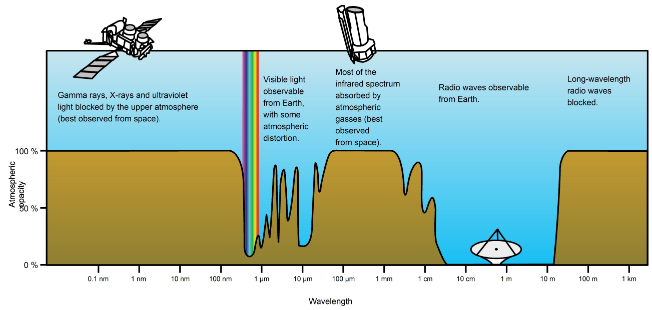
Colors that can be produced by visible light of a narrow band of wavelengths (monochromaticlight) are called pure spectral colors. Quantitatively, the regions of the visible spectrum encompassing each spectral color can be delineated roughly as:

- red – 620 to 750 nm (400-484 THz)

Note that each color can come in many shades, since the spectrum is continuous. The human eye is insensitive to electromagnetic radiation outside this range. By definition any images presented with data recorded from wavelengths other than those in the visible part of the spectrum (such as IR images of humans or animals or astronomical X-ray images) are necessarily in false color.

Visible Light and Earth's Atmosphere

Visible wavelengths pass through the "optical window", the region of the electromagnetic spectrum which allows wavelengths to pass largely unattenuated through the Earth's atmosphere (see opacity plot in. An example of this phenomenon is that clean air scatters blue light more than red wavelengths, and so the midday sky appears blue.



Atmospheric Transmittance: This is a plot of Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation. Most UV wavelengths are absorbed by oxygen and ozone in Earth's atmosphere. Observations of astronomical UV sources must be done from space.

The optical window is also called the visible window because it overlaps the human visible response spectrum. This is not coincidental as humanity's ancestors evolved vision that could make use of the most plentiful wavelengths of light.The near infrared (NIR) window lies just out of the human vision, as well as the Medium Wavelength IR (MWIR) window and the Long Wavelength or Far Infrared (LWIR or FIR) window though other animals may experience them.

A consequence of the existence of the optical window in Earth's atmosphere is the relatively balmy temperature conditions on Earth's surface. The Sun's luminosity function peaks in the visible range and light in that range is able to travel to the surface of the planet unattenuated due to the optical window. This allows visible light to heat the surface. The surface of the planet then emits energy primarily in infrared wavelengths, which has much greater difficulty escaping (and thus causing the planet to cool) due to the opacity of the atmosphere in the infrared. Earth's surface would be much cooler without this effect.

Photosynthesis

Plants, like animals, have evolved to utilize and respond to parts of the electromagnetic spectrum they are embedded in. Plants (and many bacteria) convert the light energy captured from the Sun into chemical energy that can be used to fuel the organism's activities. In plants, algae, and cyanobacteria, photosynthesis uses carbon dioxide and water, releasing oxygen as a waste product. Photosynthesis is vital for all aerobic life on Earth (such as humans and animals). The portion of the EM spectrum used by photosynthetic organisms is called the photosynthetically active region (PAR) and corresponds to solar radiation between 400 and 700 nm, substantially overlapping with the range of human vision. This is again not coincidental; the light in this range is the most plentiful to organisms on the surface of Earth because the Sun emits about half of its luminosity in this wavelength range and it is allowed to pass freely through the optical windows in Earth's atmosphere.

Ultraviolet Light

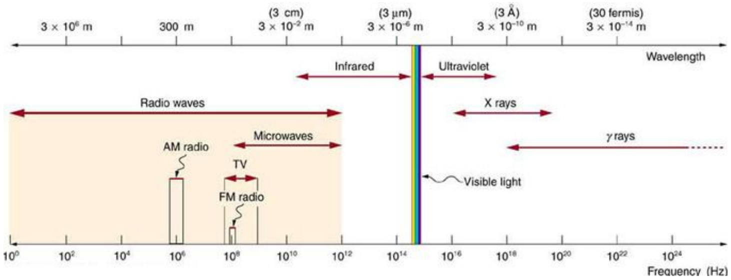
Ultraviolet (UV) light is electromagnetic radiation with a wavelength shorter than that of visible light in the range 10 nm to 400 nm.

Skills to Develop

- Identify wavelength range characteristic for ultraviolet light and its biological effects

Ultraviolet Light

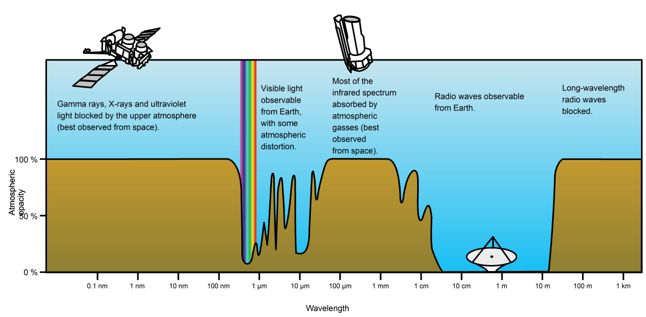
Ultraviolet (UV) light is electromagnetic radiation with a wavelength shorter than that of visible light, but longer than X-rays, that is, in the range 10 nm to 400 nm, corresponding to photon energies from 3 eV to 124 eV (1 eV = $1.6e^{-19}$ J; EM radiation with frequencies higher than those of visible light are often expressed in terms of energy rather than frequency). It is so-named because the spectrum consists of electromagnetic waves with frequencies higher than those that humans identify as the color violet. These frequencies are invisible to humans, but visible to a number of insects and birds.



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves encompass the high frequency portion of the radio section of the EM spectrum.

UV light is found in sunlight (where it constitutes about 10% of the energy in vacuum) and is emitted by electric arcs and specialized lights such as black lights. It can cause chemical reactions, and causes many substances to glow or fluoresce. Most ultraviolet is classified as non-ionizing radiation. The higher energies of the ultraviolet spectrum from wavelengths about 10 nm to 120 nm ('extreme' ultraviolet) are ionizing, but this type of ultraviolet in sunlight is blocked by normal molecular oxygen (O_2) in air, and does not reach the ground. However, the entire spectrum of ultraviolet radiation has some of the biological features of ionizing radiation, in doing far more damage to many molecules in biological systems than is accounted for by simple heating effects (an example is sunburn). These properties derive from the ultraviolet photon's power to alter chemical bonds in molecules, even without having enough energy to ionize atoms.

Although ultraviolet radiation is invisible to the human eye, most people are aware of the effects of UV on the skin, called suntan and sunburn. In addition to short wave UV blocked by oxygen, a great deal (>97%) of mid-range ultraviolet (almost all UV above 280 nm and most up to 315 nm) is blocked by the ozone layer, and like ionizing short wave UV, would cause much damage to living organisms if it penetrated the atmosphere. After atmospheric filtering, only about 3% of the total energy of sunlight at the zenith is ultraviolet, and this fraction decreases at other sun angles. Much of it is near-ultraviolet that does not cause sunburn, but is still capable of causing long term skin damage and cancer. An even smaller fraction of ultraviolet that reaches the ground is responsible for sunburn and also the formation of vitamin D (peak production occurring between 295 and 297 nm) in all organisms that make this vitamin (including humans). The UV spectrum thus has many effects, both beneficial and damaging, to human health.



Atmospheric Transmittance: This is a plot of Earth's atmospheric opacity (opposite of transmittance) to various wavelengths of electromagnetic radiation, including visible light. Visible light passes relatively unimpeded through the atmosphere in the "optical window." Most UV wavelengths are absorbed by oxygen and ozone in Earth's atmosphere. Observations of astronomical UV sources must be done from space.

Subcategories of UV Light

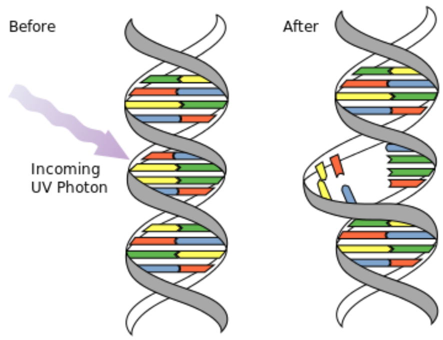
Solar UV radiation is commonly subdivided into three regions: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (220–290 nm), ranked from long to shorter wavelengths (from smaller to larger energies). Most UV-B and all UV-C is absorbed by ozone

(O_3) molecules in the upper atmosphere. Consequently, 99% of the solar UV radiation reaching the Earth's surface is UV-A.

There are other schemes for dividing UV into different categories, another common one is: near-ultraviolet (NUV – 300-400 nm), middle ultraviolet (MUV – 200-300 nm), far ultraviolet (FUV – 200-122 nm), and extreme ultraviolet (EUV- 121-10 nm).

Harmful Effects

An overexposure to UVB radiation can cause sunburn and some forms of skin cancer. In humans, prolonged exposure to solar UV radiation may result in acute and chronic health effects on the skin, eye, and immune system. Moreover, UVC can cause adverse effects that can variously be mutagenic or carcinogenic.



DNA UV Mutation: Ultraviolet photons harm the DNA molecules of living organisms in different ways. In one common damage event, adjacent thymine bases bond with each other, instead of across the "ladder. " This "thymine dimer" makes a bulge, and the distorted DNA molecule does not function properly.

The International Agency for Research on Cancer of the World Health Organization has classified all categories and wavelengths of ultraviolet radiation as a Group 1 carcinogen. This is the highest level designation for carcinogens and means that "there is enough evidence to conclude that it can cause cancer in humans. "

Beneficial Effects

UVB exposure induces the production of vitamin D in the skin. The majority of positive health effects are related to this vitamin. It has regulatory roles in calcium metabolism (which is vital for normal functioning of the nervous system, as well as for bone growth and maintenance of bone density), immunity, cell proliferation, insulin secretion, and blood pressure.

X-Rays

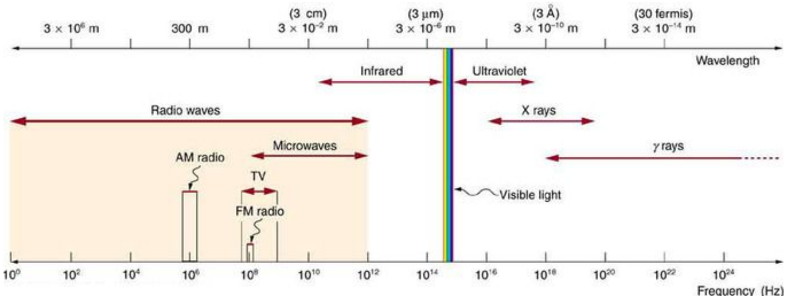
X-rays are electromagnetic waves with wavelengths in the range of 0.01 to 10 nanometers and energies in the range of 100 eV to 100 keV.

Skills to Develop

- Distinguish two categories of X-rays and their biological effects

X-Rays

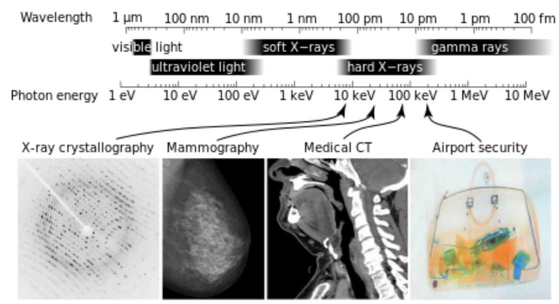
X-rays are electromagnetic waves with wavelengths in the range of 0.01 to 10 nanometers, corresponding to frequencies in the range 30 petahertz to 30 exahertz (3×10^{16} Hz to 3×10^{19} Hz) and energies in the range 100 eV to 100 keV. They are shorter in wavelength than UV rays and longer than gamma rays. In many languages, X-radiation is called Röntgen radiation, after Wilhelm Röntgen, who is usually credited as its discoverer, and who had named it X-radiation to signify an unknown type of radiation.



Electromagnetic Spectrum: The electromagnetic spectrum, showing the major categories of electromagnetic waves. The range of frequencies and wavelengths is remarkable. The dividing line between some categories is distinct, whereas other categories overlap. Microwaves encompass the high frequency portion of the radio section of the EM spectrum.

Properties and Applications

X-ray photons carry enough energy to ionize atoms and disrupt molecular bonds. This makes it a type of ionizing radiation and thereby harmful to living tissue. A very high radiation dose over a short amount of time causes radiation sickness, while lower doses can give an increased risk of radiation-induced cancer. In medical imaging this increased cancer risk is generally greatly outweighed by the benefits of the examination. The ionizing capability of X-rays can be utilized in cancer treatment to kill malignant cells using radiation therapy. It is also used for material characterization using X-ray spectroscopy.



X-Ray Spectrum and Applications: X-rays are part of the electromagnetic spectrum, with wavelengths shorter than those of visible light. Different applications use different parts of the X-ray spectrum.

X-rays with photon energies above 5 to 10 keV (below 0.2-0.1 nm wavelength), are called hard X-rays, while those with lower energy are called soft X-rays. Due to their penetrating ability, hard X-rays are widely used to image the inside of objects (e.g., in medical radiography and airport security). As a result, the term X-ray is metonymically used to refer to a radiographic image produced using this method, in addition to the method itself. Since the wavelength of hard X-rays are similar to the size of atoms, they are also useful for determining crystal structures by X-ray crystallography. By contrast, soft X-rays are easily absorbed in air and the attenuation length of 600 eV (~2 nm) X-rays in water is less than 1 micrometer.

In medical diagnostic applications, the low energy (soft) X-rays are unwanted, since they are totally absorbed by the body, increasing the radiation dose without contributing to the image. Hence, a thin metal sheet, often of aluminum, called an X-ray filter, is usually placed over the window of the X-ray tube, absorbing the low energy part in the spectrum. This is called hardening the beam since it shifts the center of the spectrum towards higher energy (or harder) X-rays.

Distinction Between X-Rays and Gamma Rays

The distinction between X-rays and gamma rays is somewhat arbitrary. The most frequent method of distinguishing between X- and gamma radiation is the basis of wavelength, with radiation shorter than some arbitrary wavelength, such as 10^{-11} m, defined as gamma rays. The electromagnetic radiation emitted by X-ray tubes generally has a longer wavelength than the radiation emitted by radioactive nuclei. Historically, therefore, an alternative means of distinguishing between the two types of radiation has been by their origin: X-rays are emitted by electrons outside the nucleus, while gamma rays are emitted by the nucleus. There is overlap between the wavelength bands of photons emitted by electrons outside the nucleus, and photons emitted by the nucleus. Like all electromagnetic radiation, the properties of X-rays (or gamma rays) depend only on their wavelength and polarization.

Gamma Rays

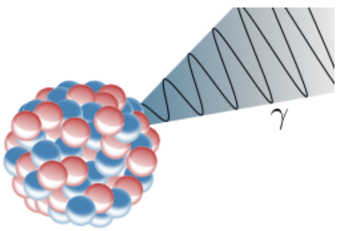
Gamma rays are very high frequency electromagnetic waves usually emitted from radioactive decay with frequencies greater than 10^{19}Hz.

Skills to Develop

- Identify wavelength range characteristic for gamma rays, noting their biological effects and distinguishing them from gamma rays

Gamma Rays

Gamma radiation, also known as gamma rays or hyphenated as gamma-rays and denoted as γ, is electromagnetic radiation of high frequency and therefore high energy. Gamma rays typically have frequencies above 10 exahertz (or $>10^{19}$ Hz), and therefore have energies above 100 keV and wavelengths less than 10 picometers (less than the diameter of an atom). However, this is not a hard and fast definition, but rather only a rule-of-thumb description for natural processes. Gamma rays from radioactive decay are defined as gamma rays no matter what their energy, so that there is no lower limit to gamma energy derived from radioactive decay. Gamma decay commonly produces energies of a few hundred keV, and almost always less than 10 MeV.



Gamma Decay: Illustration of an emission of a gamma ray (γ) from an atomic nucleus

Gamma rays are ionizing radiation and are thus biologically hazardous. They are classically produced by the decay from high energy states of atomic nuclei, a process called gamma decay, but are also created by other processes. Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium during its gamma decay. Villard's radiation was named "gamma rays" by Ernest Rutherford in 1903.

Gamma Ray Sources

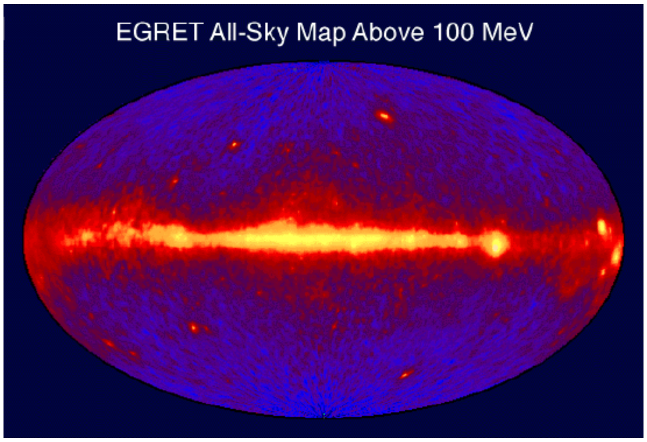
Natural sources of gamma rays on Earth include gamma decay from naturally occurring radioisotopes such as potassium-40, and also as a secondary radiation from various atmospheric interactions with cosmic ray particles. Some rare terrestrial natural sources that produce gamma rays that are not of a nuclear origin, are lightning strikes and terrestrial gamma-ray flashes, which produce high energy emissions from natural high-energy voltages. Gamma rays are produced by a number of astronomical processes in which very high-energy electrons are produced. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. A large fraction of such astronomical gamma rays are screened by Earth's atmosphere and must be detected by spacecraft. Notable artificial sources of gamma rays include fission such as occurs in nuclear reactors, and high energy physics experiments, such as neutral pion decay and nuclear fusion.

Gamma Rays vs. X-Rays

Gamma rays have characteristics identical to X-rays of the same frequency—they differ only in source. At higher frequencies, γ rays are more penetrating and more damaging to living tissue. They have many of the same uses as X-rays, including cancer therapy. Gamma radiation from radioactive materials is used in nuclear medicine.

The distinction between X-rays and gamma rays has changed in recent decades. Originally, the electromagnetic radiation emitted by X-ray tubes almost invariably had a longer wavelength than the radiation (gamma rays) emitted by radioactive nuclei. Older literature distinguished between X- and gamma radiation on the basis of wavelength, with radiation shorter than some arbitrary wavelength, such as 10^{-11} m, defined as gamma rays. However, with artificial sources now able to duplicate any electromagnetic radiation that originates in the nucleus, as well as far higher energies, the wavelengths characteristic of radioactive gamma ray sources vs. other types, now completely overlap. Thus, gamma rays are now usually distinguished by their origin: X-rays are emitted by definition by electrons outside the nucleus, while gamma rays are emitted by the nucleus.

Exceptions to this convention occur in astronomy, where gamma decay is seen in the afterglow of certain supernovas, but other high energy processes known to involve other than radioactive decay are still classed as sources of gamma radiation. A notable example is extremely powerful bursts of high-energy radiation normally referred to as long duration gamma-ray bursts, which produce gamma rays by a mechanism not compatible with radioactive decay. These bursts of gamma rays, thought to be due to the collapse of stars called hypernovas, are the most powerful events so far discovered in the cosmos. Astrophysical processes are the only sources for very high energy gamma rays (~100 MeV).



Gamma Ray Sky Map: This is an image of the entire sky in 100 MeV or greater gamma rays as seen by the EGRET instrument aboard the CGRO spacecraft. Bright spots within the galactic plane are pulsars (spinning neutron stars with strong magnetic fields), while those above and below the plane are thought to be quasars (galaxies with supermassive black holes actively accreting matter).

Health Effects

All ionizing radiation causes similar damage at a cellular level, but because rays of alpha particles and beta particles are relatively non-penetrating, external exposure to them causes only localized damage (e.g., radiation burns to the skin). Gamma rays and neutrons are more penetrating, causing diffuse damage throughout the body (e.g., radiation sickness, cell's DNA damage, cell death due to damaged DNA, increasing incidence of cancer) rather than burns. External radiation exposure should also be distinguished from internal exposure, due to ingested or inhaled radioactive substances, which, depending on the substance's chemical nature, can produce both diffuse and localized internal damage. The most biological damaging forms of gamma radiation occur at energies between 3 and 10 MeV.

Key Points

- The lowest frequency portion of the electromagnetic spectrum is designated as "radio," generally considered to have wavelengths within 1 millimeter to 100 kilometers or frequencies within 300 GHz to 3 kHz.
- There is a wide range of subcategories contained within radio including AM and FM radio. Radio waves can be generated by natural sources such as lightning or astronomical phenomena; or by artificial sources such as broadcast radio towers, cell phones, satellites and radar.
- AM radio waves are used to carry commercial radio signals in the frequency range from 540 to 1600 kHz. The abbreviation AM stands for amplitude modulation—the method for placing information on these waves. AM waves have constant frequency, but a varying amplitude.
- FM radio waves are also used for commercial radio transmission in the frequency range of 88 to 108 MHz. FM stands for frequency modulation, which produces a wave of constant amplitude but varying frequency.
- The microwave region of the electromagnetic (EM) spectrum is generally considered to overlap with the highest frequency (shortest wavelength) radio waves.
- The prefix "micro-" in "microwave" is not meant to suggest a wavelength in the micrometer range. It indicates that microwaves are "small" compared to waves used in typical radio broadcasting in that they have shorter wavelengths.
- The microwave portion of the electromagnetic spectrum can be subdivided into three ranges listed below from high to low frequencies: extremely high frequency (30 to 300 GHz), super high frequency (3 to 30 GHz), and ultra-high frequency (300 MHz to 3 GHz).
- Microwave sources include artificial devices such as circuits, transmission towers, radar, masers, and microwave ovens, as well as natural sources such as the Sun and the Cosmic Microwave Background.

- Microwaves can also be produced by atoms and molecules. They are, for example, a component of electromagnetic radiation generated by thermal agitation. The thermal motion of atoms and molecules in any object at a temperature above absolute zero causes them to emit and absorb radiation.
- Infrared light includes most of the thermal radiation emitted by objects near room temperature. Infrared light is emitted or absorbed by molecules when they change their rotational-vibrational movements.
- The infrared portion of the spectrum can be divided into three regions in wavelength: far-infrared, from 300 GHz (1 mm) to 30 THz (10 μm); mid-infrared, from 30 to 120 THz (10 to 2.5 μm); and near-infrared, from 120 to 400 THz (2,500 to 750 nm).
- Infrared radiation is popularly known as " heat radiation," but light and electromagnetic waves of any frequency will heat surfaces that absorb them.
- The concept of emissivity is important in understanding the infrared emissions of objects. This is a property of a surface which describes how its thermal emissions deviate from the ideal of a black body.
- Infrared radiation can be used to remotely determine the temperature of objects (if the emissivity is known). This is termed thermography, mainly used in military and industrial applications.
- Visible light is produced by vibrations and rotations of atoms and molecules, as well as by electronic transitions within atoms and molecules. We say the atoms and molecules are excited when they absorb and relax when they emit through electronic transitions.
- This figure shows the visible part of the spectrum, together with the colors associated with particular pure wavelengths. Red light has the lowest frequencies and longest wavelengths, while violet has the highest frequencies and shortest wavelengths.
- Colors that can be produced by visible light of a narrow band of wavelengths are called pure spectral colors. They can be delineated roughly in wavelength as: violet (380-450 nm), blue (450-495 nm), green (495-570 nm), yellow (570-590 nm), orange (590-620 nm), and red (620 to 750 nm).
- Visible wavelengths pass through the optical window, the Earth's atmosphere allows this region of the electromagnetic spectrum to pass through largely unattenuated (see opacity plot in.
- The portion of the EM spectrum used by photosynthesic organisms is called the photosynthetically active region (PAR) and corresponds to solar radiation between 400 and 700 nm, substantially overlapping with the range of human vision.
- Ultraviolet light gets its name because the spectrum consists of electromagnetic waves with frequencies higher than those that humans identify as the color violet.
- Most UV is non- ionizing radiation, though UV with higher energies (10-120 nm) is ionizing. All UV can have harmful effects on biological matter (such as causing cancers) with the highest energies causing the most damage.
- The danger posed by lower energy UV radiation is derived from the ultraviolet photon 's power to alter chemical bonds in molecules, even without having enough energy to ionize atoms.
- Solar UV radiation is commonly subdivided into three regions: UV-A (320–400 nm), UV-B (290–320 nm), and UV-C (220–290 nm), ranked from long to shorter wavelengths (from smaller to larger energies).
- Most UV-B and all UV-C is absorbed by ozone (O_3) molecules in the upper atmosphere. Consequently, 99% of the solar UV radiation reaching the Earth's surface is UV-A.
- X-rays have shorter wavelengths (higher energy) than UV waves and, generally, longer wavelengths (lower energy) than gamma rays. Sometimes X-rays are called Röntgen radiation, after Wilhelm Röntgen, who is usually credited as their discoverer.
- Because X-rays have very high energy they are known as ionizing radiation and can harm living tissue. A very high radiation dose over a short amount of time causes radiation sickness, while lower doses can give an increased risk of radiation-induced cancer.
- Lower doses of X-ray radiation can be very effectively used in medical radiography and X-ray spectroscopy. In the case of medical radiography, the benefits of using X-rays for examination far outweighs the risk.
- X-rays are broken up into broad two categories: hard X-rays with energies above 5-10 keV (below 0.2-0.1 nm wavelength) and soft X-rays with energies 100 eV – 5 keV (10 – 0.1 nm wavelength). Hard X-rays are more useful for radiography because they pass through tissue.
- The distinction between X-rays and gamma rays is somewhat arbitrary and there is substantial overlap at the high energy boundary. However, in general they are distinguished by their source, with gamma rays originating from the nucleus and X-rays from the electrons in the atom.
- Gamma rays are the highest energy EM radiation and typically have energies greater than 100 keV, frequencies greater than 10^{19} Hz, and wavelengths less than 10 picometers.

- Gamma rays from radioactive decay are defined as gamma rays no matter what their energy, so that there is no lower limit to gamma energy derived from radioactive decay. Gamma decay commonly produces energies of a few hundred keV, and almost always less than 10 MeV.
- Gamma rays have characteristics identical to X-rays of the same frequency—they differ only in source. Gamma rays are usually distinguished by their origin: X-rays are emitted by definition by electrons outside the nucleus, while gamma rays are emitted by the nucleus.
- Natural sources of gamma rays include gamma decay from naturally occurring radioisotopes such as potassium-40, and also as a secondary radiation from atmospheric interactions with cosmic ray particles. Exotic astrophysical processes will also produce gamma rays.
- Gamma rays are ionizing radiation and are thus biologically hazardous. The most biological damaging forms of gamma radiation occur at energies between 3 and 10 MeV.

Key Terms

- **AM radio waves**: Waves used to carry commercial radio signals between 540 and 1600 kHz. Information is carried by amplitude variation, while the frequency remains constant.
- **FM radio waves**: Waves used to carry commercial radio signals between 88 and 108 MHz. Information is carried by frequency modulation, while the signal amplitude remains constant.
- **radio waves**: Designates a portion of the electromagnetic spectrum having frequencies ranging from 300 GHz to 3 kHz, or equivalently, wavelengths from 1 millimeter to 100 kilometers.
- **terahertz radiation**: Electromagnetic waves with frequencies around one terahertz.
- **thermal agitation**: The thermal motion of atoms and molecules in any object at a temperature above absolute zero, causing them to emit and absorb radiation.
- **radar**: A method of detecting distant objects and determining their position, velocity, or other characteristics by analysis of sent radio waves (usually microwaves) reflected from their surfaces.
- **emissivity**: The energy-emitting propensity of a surface, usually measured at a specific wavelength.
- **thermography**: Any of several techniques for the remote measurement of the temperature variations of a body, especially by creating images produced by infrared radiation.
- **thermal radiation**: The electromagnetic radiation emitted from a body as a consequence of its temperature; increasing the temperature of the body increases the amount of radiation produced, and shifts it to shorter wavelengths (higher frequencies) in a manner explained only by quantum mechanics.
- **spectral color**: a color that is evoked by a single wavelength of light in the visible spectrum, or by a relatively narrow band of wavelengths. Every wavelength of light is perceived as a spectral color, in a continuous spectrum; the colors of sufficiently close wavelengths are indistinguishable.
- **optical window**: the optical portion of the electromagnetic spectrum that passes through the atmosphere all the way to the ground. The window runs from around 300 nanometers (ultraviolet-C) at the short end up into the range the eye can use, roughly 400-700 nm and continues up through the visual infrared to around 1100 nm, which is thermal infrared.
- **visible light**: the part of the electromagnetic spectrum, between infrared and ultraviolet, that is visible to the human eye
- **ozone layer**: A region of the stratosphere, between 15 and 30 kilometres in altitude, containing a relatively high concentration of ozone; it absorbs most solar ultraviolet radiation.
- **ionizing radiation**: high-energy radiation that is capable of causing ionization in substances through which it passes; also includes high-energy particles
- **non-ionizing radiation**: Radiation that does not cause atmospheric ionization; electrically neutral radiation.
- **X-ray spectroscopy**: The use of an X-ray spectrometer for chemical analysis.
- **x-ray crystallography**: A technique in which the patterns formed by the diffraction of X-rays on passing through a crystalline substance yield information on the lattice structure of the crystal, and the molecular structure of the substance.
- **radiograph**: An image, often a photographic negative, produced by radiation other than normal light; especially an X-ray photograph.
- **gamma ray**: A very high frequency (and therefore very high energy) electromagnetic radiation emitted as a consequence of radioactivity.
- **gamma decay**: A nuclear reaction with the emission of a gamma ray.

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3.2: Electromagnetic Waves and their Properties

learning objectives

- Explain the meaning and importance of Maxwell's equations

Maxwell's Equations

Maxwell's equations are a set of four partial differential equations that, along with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits.

Named after esteemed physicist James Clerk Maxwell, the equations describe the creation and propagation of electric and magnetic fields. Fundamentally, they describe how electric charges and currents create electric and magnetic fields, and how they affect each other.

Maxwell's equations can be divided into two major subsets. The first two, Gauss's law and Gauss's law for magnetism, describe how fields emanate from charges and magnets respectively. The other two, Faraday's law and Ampere's law with Maxwell's correction, describe how induced electric and magnetic fields circulate around their respective sources.

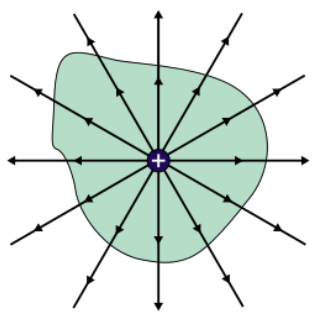
Each of Maxwell's equations can be looked at from the "microscopic" perspective, which deals with total charge and total current, and the "macroscopic" set, which defines two new auxiliary fields that allow one to perform calculations without knowing microscopic data like atomic-level charges.

Gauss's Law

Gauss's law relates an electric field to the charge(s) that create(s) it. The field (E) points towards negative charges and away from positive charges, and from the microscopic perspective, is related to charge density (ρ) and vaccuum permittivity (ε_0, or permittivity of free space) as:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \tag{3.2.1}$$

Gauss's Law basically says that a net amount of charge contained within a region of space will generate an electric field that emanates through the surface that surrounds that region.

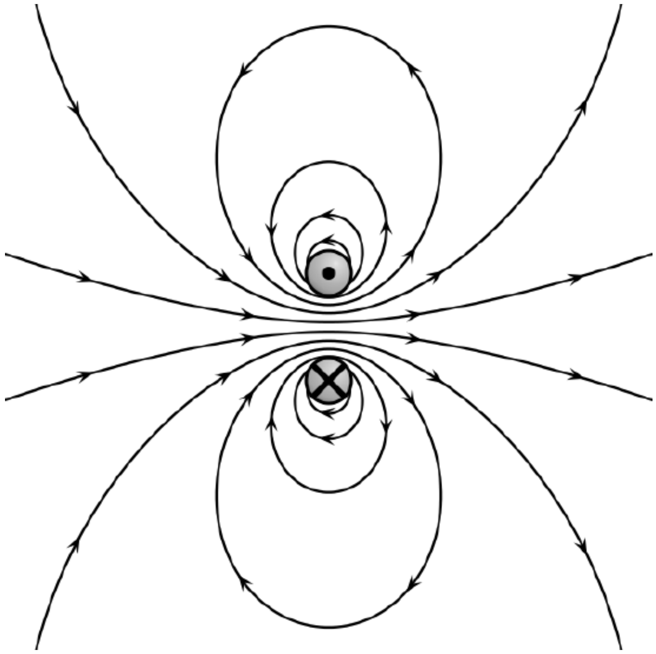


Example of Gauss's Law: A positive charge contained within a region of space creates an electric field that emanates from the surface of that region.

Gauss's Law for Magnetism

Gauss's law for magnetism states that there are *no* "magnetic charges (or monopoles)" analogous to electric charges, and that magnetic fields are instead generated by magnetic *dipoles*. Such dipoles can be represented as loops of current, but in many ways are similar in appearance to positive and negative "magnetic charges" that are inseparable and thus have no formal net "magnetic charge."

Magnetic field lines form loops such that all field lines that go into an object leave it at some point. Thus, the total magnetic flux through a surface surrounding a magnetic dipole is always zero.



Field lines caused by a magnetic dipole: The field lines created by this magnetic dipole either form loops or extend infinitely.

The differential form of Gauss's law for magnetic for magnetism is

$$\nabla \cdot \mathbf{B} = \mathbf{0} \tag{3.2.2}$$

Faraday's Law

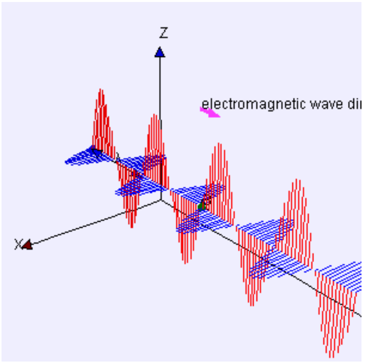
Faraday's law describes how a time-varying magnetic field (or flux) induces an electric field. The principle behind this phenomenon is used in many electric generators. Both macroscopic and microscopic differential equations are the same, relating electric field (E) to the time-partial derivative of magnetic field (B):

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial \mathbf{t}} \tag{3.2.3}$$

Ampere's Circuital Law (with Maxwell's correction)

Ampere's law originally stated that magnetic field could be created by electrical current. Maxwell added a second source of magnetic fields in his correction: a changing electric field (or flux), which would induce a magnetic field even in the absence of an electrical current. He named the changing electric field "displacement current."

Maxwell's correction shows that self-sustaining electromagnetic waves (light) can travel through empty space even in the absence of moving charges or currents, with the electric field component and magnetic field component each continually changing and each perpetuating the other.



Electromagnetic Waves: Electric (red) and magnetic (blue) waves propagate in phase sinusoidally, and perpendicularly to one another.

The microscopic approach to the Maxwell-corrected Ampere's law relates magnetic field (B) to current density (J, or current per unit cross sectional area) and the time-partial derivative of electric field (E):

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{3.2.4}$$

The Production of Electromagnetic Waves

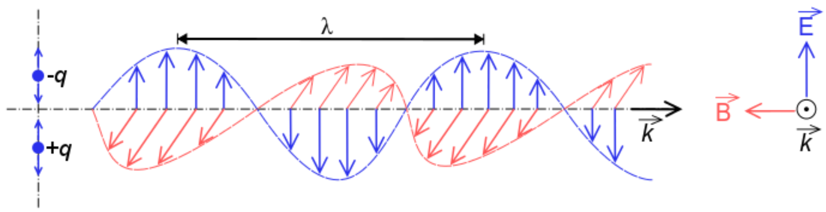
Electromagnetic waves are the combination of electric and magnetic field waves produced by moving charges.

learning objectives

- Explain the self-perpetuating behavior of an electromagnetic wave

Electromagnetic waves

Electromagnetic radiation, is a form of energy emitted by moving charged particles. As it travels through space it behaves like a wave, and has an oscillating electric field component and an oscillating magnetic field. These waves oscillate perpendicularly to and in phase with one another.



Electromagnetic Wave: Electromagnetic waves are a self-propagating transverse wave of oscillating electric and magnetic fields. The direction of the electric field is indicated in blue, the magnetic field in red, and the wave propagates in the positive x-direction. Notice that the electric and magnetic field waves are in phase.

The creation of all electromagnetic waves begins with a charged particle. This charged particle creates an electric field (which can exert a force on other nearby charged particles). When it accelerates as part of an oscillatory motion, the charged particle creates ripples, or oscillations, in its electric field, and also produces a magnetic field (as predicted by Maxwell's equations).

Once in motion, the electric and magnetic fields created by a charged particle are self-perpetuating—time-dependent changes in one field (electric or magnetic) produce the other. This means that an electric field that oscillates as a function of time will produce a magnetic field, and a magnetic field that changes as a function of time will produce an electric field. Both electric and magnetic fields in an electromagnetic wave will fluctuate in time, one causing the other to change.

Electromagnetic waves are ubiquitous in nature (i.e., light) and used in modern technology—AM and FM radio, cordless and cellular phones, garage door openers, wireless networks, radar, microwave ovens, etc. These and many more such devices use electromagnetic waves to transmit data and signals.

All the above sources of electromagnetic waves use the simple principle of moving charge, which can be easily modeled. Placing a coin in contact with both terminals of a 9-volt battery produces electromagnetic waves that can be detected by bringing the antenna of a radio (tuned to a static-producing station) within a few inches of the point of contact.

Energy and Momentum

Electromagnetic waves have energy and momentum that are both associated with their wavelength and frequency.

learning objectives

- Relate energy of an electromagnetic wave with the frequency and wavelength

Electromagnetic radiation can essentially be described as photon streams. These photons are strictly defined as massless, but have both energy and surprisingly, given their lack of mass, momentum, which can be calculated from their wave properties.

Waves were poorly understood until the 1900s, when Max Planck and Albert Einstein developed modern corrections to classical theory.

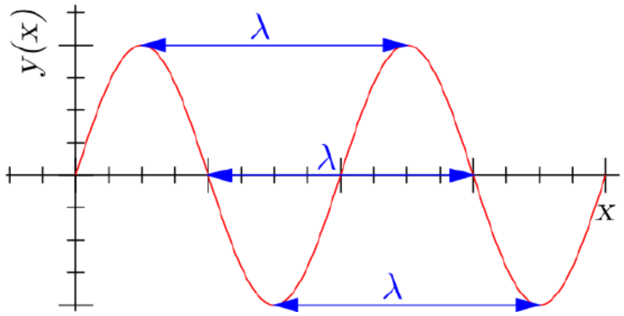
Planck theorized that “black bodies” (thermal radiators) and other forms of electromagnetic radiation existed not as spectra, but in discrete, “quantized” form. In other words, there were only certain energies an electromagnetic wave could have. In his work he developed what is now known as “Planck’s constant,” which is approximately equal to 6.626×10^{-34} J·s.

Energy

The energy (E) of a photon can be related to its frequency (f) by Planck’s constant (h):

$$\mathrm{E=hf=\frac{hc}{\lambda}} \tag{3.2.5}$$

The ratio of speed of light (c) to wavelength (λ) can be substituted in place of f to give the same equation to energy in different terms. Note that energy cannot take any value: it can only exist in increments of frequency times Planck’s constant (or Planck’s constant times c divided by wavelength). Energy of a wave is therefore “quantized. ”



Wavelength: Wavelength of the sinusoidal function is represented by λ.

Momentum

Momentum is classically defined as the product of mass and velocity and thus would intuitively seem irrelevant to a discussion of electromagnetic radiation, which is both massless and composed of waves.

However, Einstein proved that light can act as particles in some circumstances, and that a wave-particle duality exists. And, given that he related energy and mass ($E=mc^2$), it becomes more conceivable that a wave (which has an energy value) not only has an equation to mass but a momentum as well.

And indeed, Einstein proved that the momentum (p) of a photon is the ratio of its energy to the speed of light.

$$\mathrm{p=\frac{E}{c}=\frac{hf}{c}=\frac{h}{\lambda}} \tag{3.2.6}$$

Substituting E with hc/λ cancels the c terms, making momentum also equal to the simple ratio of Planck’s constant to wavelength.

The Speed of Light

The speed of light in a vacuum is one of the most fundamental constant in physics, playing a pivotal role in modern physics.

learning objectives

- Relate speed of light with the index of refraction of the medium

The Speed of Light

The speed of light is generally a point of comparison to express that something is fast. shows a scale representation of the time it takes a beam of light to reach the moon from Earth. But what exactly is the speed of light?

Light Going from Earth to the Moon: A beam of light is depicted travelling between the Earth and the Moon in the time it takes a light pulse to move between them: 1.255 seconds at their mean orbital (surface-to-surface) distance. The relative sizes and separation of the Earth–Moon system are shown to scale.

It is just that: the speed of a photon or light particle. The speed of light in a vacuum (commonly written as c) is 299,792,458 meters per second. This is a universal physical constant used in many areas of physics. For example, you might be familiar with the equation:

$$\mathrm{E} = \mathrm{mc}^2 \tag{3.2.7}$$

where E = Energy and m = mass. This is known as the mass-energy equivalence, and it uses the speed of light to interrelate space and time. This not only explains the energy a body of mass contains, but also explains the hindrance mass has on speed.

There are many uses for the speed of light in a vacuum, such as in special relativity, which says that c is the natural speed limit and nothing can move faster than it. However, we know from our understanding of physics (and previous atoms) that the speed at which something travels also depends on the medium through which it is traveling. The speed at which light propagates through transparent materials (air, glass, etc.,) is dependent on the refractive index of that material, n:

$$\mathrm{v} = \frac{\mathrm{c}}{\mathrm{n}} \tag{3.2.8}$$

where v = actual velocity of light moving through the medium, c = speed of light in a vacuum, and n = refractive index of medium. The refractive index of air is about 1.0003, and from this equation we can find that the speed of visible light in air is about 90 km/s slower than c.

As mentioned earlier, the speed of light (usually of light in a vacuum) is used in many areas of physics. Below is an example of an application of the constant c.

The Lorentz Factor

Fast-moving objects exhibit some properties that are counterintuitive from the perspective of classical mechanics. For example, length contracts and time dilates (runs slower) for objects in motion. The effects are typically minute, but are noticeable at sufficiently high speeds. The Lorentz factor (γ) is the factor by which length shortens and time dilates as a function of velocity (v):

$$\gamma = \left(1 - \mathrm{v}^2/\mathrm{c}^2\right)^{-1/2} \gamma = \left(1 - \mathrm{v}^2/\mathrm{c}^2\right)^{-1/2} \gamma = \left(1 - \mathrm{v}^2/\mathrm{c}^2\right)^{-1/2} \tag{3.2.9}$$

At low velocities, the quotient of v^2/c^2 is sufficiently close to 0 such that γ is approximately 1. However, as velocity approaches c, γ increases rapidly towards infinity.

The Doppler Effect

The Doppler Effect is the change in a wave's perceived frequency that results from the source's motion, the observer, and the medium.

learning objectives

- Give examples of daily observations of the Doppler effect

The Doppler Effect

The Doppler effect is a periodic event's change in frequency for an observer in motion relative to the event's source. Typically, this periodic event is a wave.

Most people have experienced the Doppler effect in action. Consider an emergency vehicle in motion, sounding its siren. As it approaches an observer, the pitch of the sound (its frequency) sounds higher than it actually is. When the vehicle reaches the observer, the pitch is perceived as it actually is. When the vehicle continues away from the observer, the pitch is perceived as lower than it actually is. From the perspective of an observer inside the vehicle, the pitch of the siren is constant.

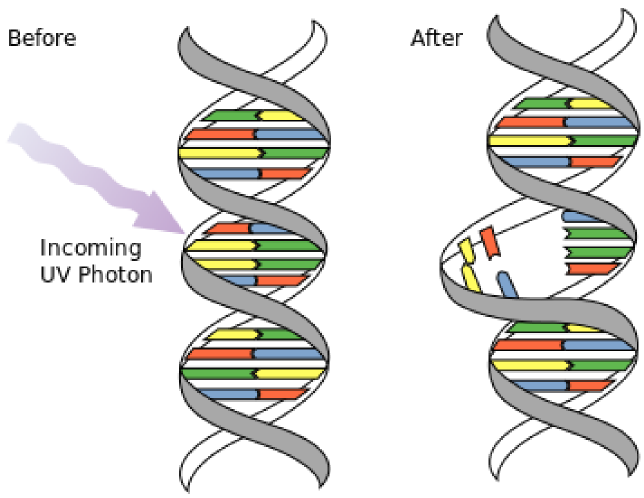
The Doppler Effect and Sirens: Waves emitted by a siren in a moving vehicle

The difference in the perceived pitch depending on observer location can be explained by the fact that the siren's position changes as it emits waves. A wave of sound is emitted by a moving vehicle every millisecond. The vehicle 'chases' each wave in one direction. By the time the next wave is emitted, it is closer (relative to an onlooker ahead of the vehicle) to the previous wave than the wave's frequency would suggest. Relative to an onlooker behind the vehicle, the second wave is further from the first wave than one would expect, which suggests a lower frequency.

The Doppler effect can be caused by any kind of motion. In the example above, the siren moved relative to a stationary observer. If the observer moves relative to the stationary siren, the observer will notice the Doppler effect on the pitch of the siren. Finally, if the medium through which the waves propagate moves, the Doppler effect will be noticed even for a stationary observer. An example of this phenomenon is wind.

Quantitatively, the Doppler effect can be characterized by relating the frequency perceived (f) to the velocity of waves in the medium (c), the velocity of the receiver relative to the medium (v_r), the velocity of the source relative to the medium (v_s), and the actual emitted frequency (f_0):

$$f=\left(\frac{c+v_r}{c+v_s}\right)f_0 \tag{3.2.10}$$



The Doppler Effect: Wavelength change due to the motion of source

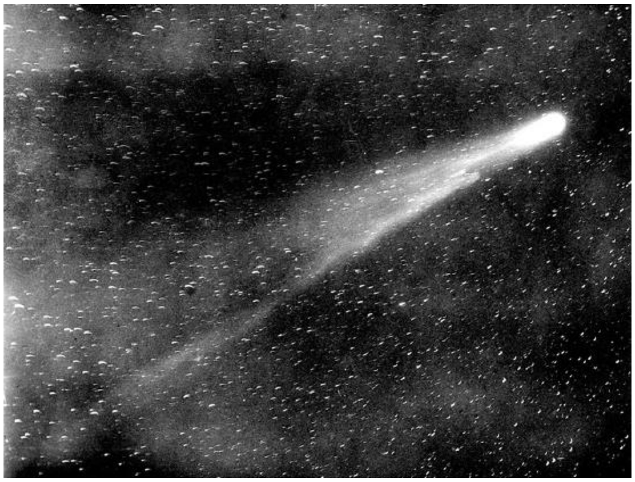
Momentum Transfer and Radiation Pressure Atom

Radiation pressure is the pressure exerted upon any surface exposed to electromagnetic (EM) radiation.

learning objectives

- Explain formation of radiation pressure

Radiation pressure is the pressure exerted upon any surface exposed to electromagnetic (EM) radiation. EM radiation (or photon, which is a quantum of light) carries momentum; this momentum is transferred to an object when the radiation is absorbed or reflected. Perhaps one of the most well know examples of the radiation pressure would be comet tails. Haley's comet is shown in.



Halley's Comet: As a comet approaches the inner Solar System, solar radiation causes the volatile materials within the comet to vaporize and stream out of the nucleus. The streams of dust and gas thus released form an atmosphere around the comet (called the coma), and the force exerted on the coma by the Sun's radiation pressure and solar wind cause the formation of an enormous tail that points away from the Sun.

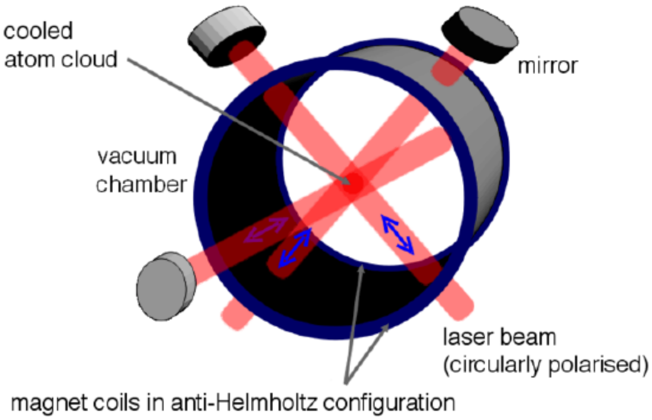
Although radiation pressure can be understood using classical electrodynamics, here we will examine the quantum mechanical argument. From the perspective of quantum theory, light is made of photons: particles with zero mass but which carry energy and – importantly in this argument – momentum. According to special relativity, because photons are devoid of mass, their energy (E) and momentum (p) are related by E=pc.

Now consider a beam of light perpendicularly incident on a surface, and let us assume the beam of light is totally absorbed. The momentum the photons carry is a conserved quantity (i.e., it cannot be destroyed) so it must be transferred to the surface; thus the absorption of the light beam causes the surface to gain momentum. Newton's Second Law tells us that force equals rate of change of momentum; thus during each second, the surface experiences a force (or pressure, as pressure is force per unit area) due to the momentum the photons transfer to it.

This gives us: pressure = momentum transferred per second per unit area = energy deposited per second per unit area / c = I/c, (where I is the intensity of the beam of light).

Laser Cooling

There are many variations of laser cooling, but they all use radiation pressure to remove energy from atomic gases (and therefore cool the sample). In laser cooling (sometimes called Doppler cooling), the frequency of light is tuned slightly below an electronic transition in the atom. Because light is detuned to the "red" (i.e., at lower frequency) of the transition, the atoms will absorb more photons if they move towards the light source, due to the Doppler effect. Thus if one applies light from two opposite directions, the atoms will always scatter more photons from the laser beam pointing opposite to their direction of motion (typical setups applies three opposing pairs of laser beams as in).



The Magneto Optical Trap: Experimental setup of Magneto Optical Trap (MOT), which uses radiation pressure to cool atomic species. Atoms are slowed down by absorbing (and emitting) photons.

In each scattering event, the atom loses a momentum equal to the momentum of the photon. If the atom (which is now in the excited state) then emits a photon spontaneously, it will be kicked by the same amount of momentum, only in a random direction. Since the initial momentum loss was opposite to the direction of motion (while the subsequent momentum gain was in a random direction), the overall result of the absorption and emission process is to reduce the speed of the atom. If the absorption and emission are repeated many times, the average speed (and therefore the kinetic energy) of the atom will be reduced. Since the temperature of a group of atoms is a measure of the average random internal kinetic energy, this is equivalent to cooling the atoms. Simple laser cooling setups can produce a cold sample of atomic gases at around 1mK (=10^{-3} K) starting from a room temperature gas.

Key Points

- Maxwell's four equations describe how electric charges and currents create electric and magnetic fields, and how they affect each other.
- Gauss's law relates an electric field to the charge(s) that create(s) it.
- Gauss's law for magnetism states that there are no "magnetic charges" analogous to electric charges, and that magnetic fields are instead generated by magnetic dipoles.
- Faraday's law describes how a time-varying magnetic field (or flux) induces an electric field. The principle behind this phenomenon is used in many electric generators.
- Ampere 's law originally stated that a magnetic field is created by an electrical current. Maxwell added that a changing electric flux can also generate a magnetic field.
- Electromagnetic waves consist of both electric and magnetic field waves. These waves oscillate in perpendicular planes with respect to each other, and are in phase.
- The creation of all electromagnetic waves begins with an oscillating charged particle, which creates oscillating electric and magnetic fields.
- Once in motion, the electric and magnetic fields that a charged particle creates are self-perpetuating: time-dependent changes in one field (electric or magnetic) produce the other.
- Max Planck proved that energy of a photon (a stream of which is an electromagnetic wave) is quantized and can exist in multiples of "Planck's constant" (denoted as h, approximately equal to 6.626×10^{-34} J·s).
- $\mathrm{E}=\mathrm{hf}=\frac{\mathrm{hc}}{\lambda}$ describes the energy (E) of a photon as a function of frequency (f), or wavelength (λ).
- $\mathrm{p}=\frac{\mathrm{E}}{\mathrm{c}}=\frac{\mathrm{hf}}{\mathrm{c}}=\frac{\mathrm{h}}{\lambda}$ describes the momentum (p) of a photon as a function of its energy, frequency, or wavelength.
- The maximum possible value for the speed of light is that of light in a vacuum, and this speed is used for a constant in many area of physics.
- c is the symbol used to represent the speed of light in a vacuum, and its value is 299,792,458 meters per second.
- When light travels through medium, its speed is hindered by the index of refraction of that medium. Its actual speed can be found with: $v=\frac{c}{n}$.
- The Doppler effect is very commonly observed in action.
- The Doppler effect can be observed in the apparent change in pitch of a siren on an emergency vehicle, according to a stationary observer.
- The observer will notice the Doppler effect on the pitch of the stationary siren when moving relative to its pitch, or if the medium moves when the observer is stationary.
- Photons carry momentum (p = E/c). When photons are absorbed or reflected on a surface, the surface receives momentum kicks. This momentum transfer leads to radiation pressure.
- Electromagnetic radiation applies radiation pressure equal to the Intensity (of light beam) divided by c (speed of light).
- Laser cooling uses radiation pressure to remove energy from atomic gases. The technique can produce cold samples of gases at 1mK or so.

Key Terms

- **differential equation**: An equation involving the derivatives of a function.
- **flux**: A quantitative description of the transfer of a given vector quantity through a surface. In this context, we refer to the electric flux and magnetic flux.
- **electromagnetic wave**: A wave of oscillating electric and magnetic fields.

- **phase**: Waves are said to be “in phase” when they begin at the same part (e.g., crest) of their respective cycles.
- **photon**: The quantum of light and other electromagnetic energy, regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime.
- **wavelength**: The length of a single cycle of a wave, as measured by the distance between one peak or trough of a wave and the next; it is often designated in physics as λ, and corresponds to the velocity of the wave divided by its frequency.
- **frequency**: The quotient of the number of times n a periodic phenomenon occurs over the time t in which it occurs: $f = n / t$.
- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **refractive index**: The ratio of the speed of light in air or vacuum to that in another medium.
- **doppler effect**: Apparent change in frequency of a wave when the observer and the source of the wave move relative to each other.
- **classical electrodynamics**: A branch of theoretical physics that studies consequences of the electromagnetic forces between electric charges and currents.

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3.3: Applications of EM Waves

learning objectives

- Discuss wireless technologies and their applications

Wireless communication is the transfer of information between two or more points that are not connected by an electrical conductor. The term is commonly used in the telecommunications industry to refer to telecommunications systems (e.g., radio transmitters and receivers, remote controls, etc.) that use some form of energy (e.g., radio waves, acoustic energy, etc.) to transfer information without the use of wires. Information is transferred in this manner over both short and long distances. Wireless operations permit services, such as long-range communications, that are otherwise impossible (or impractical) to implement with the use of wires.

The most common wireless technologies use electromagnetic wireless telecommunications, such as radio or infra-red signals. With infra-red waves, distances are short (such as a few meters for television remote control) while radio waves can reach as far as thousands or even millions of kilometers for deep-space radio communications. It encompasses various types of fixed, mobile, and portable applications, including two-way radios, cellular telephones, personal digital assistants (PDAs), and wireless networking. Other examples of applications of radio wireless technology include GPS units, garage door openers, wireless computer mice, keyboards and headsets, headphones, radio receivers, satellite television, broadcast television, and cordless telephones. Less common methods of achieving wireless communications include the use of light, sound, magnetic, or electric fields.

Two cellular phones: The Qualcomm QCP-2700, a mid-1990s candybar style phone, and an iPhone 4S, a current production smartphone.

One of the best-known examples of wireless technology is the mobile (or cellular) phone, with more than 4.6 billion mobile cellular subscriptions worldwide as of the end of 2010 (examples of such phones are shown in). These wireless devices use radio waves to enable their users to make phone calls from many locations worldwide. They can be used within range of the mobile telephone sites that house the necessary equipment to transmit and receive the radio signals these devices emit. Wireless data communications are also an essential component of mobile computing. The various available technologies differ in local availability, coverage range, and performance. In some circumstances, users must be able to employ multiple connection types and switch between them.

To simplify the experience for the user, connection manager software is available, or a mobile VPN can be utilized to handle the multiple connections as a secure, single virtual network. One popular supporting technology is Wi-Fi, a wireless local area network that enables portable computing devices to connect easily to the Internet. Standardized as IEEE 802.11 a,b,g,n, Wi-Fi approaches speeds of some types of wired Ethernet. Wi-Fi has become the de facto standard for access in private homes, within offices, and at public hotspots. Some businesses charge customers a monthly fee for the service, while others offer it for free in an effort to increase sales of their goods.

Cellular data service offers coverage within a range of 10-15 miles from the nearest cell site. Speeds have increased as technologies have evolved, from earlier technologies such as GSM, CDMA and GPRS, to 3G networks such as W-CDMA, EDGE or CDMA2000. Mobile Satellite Communications may be used where other wireless connections are unavailable, such as in largely rural areas or remote locations. Satellite communications are especially important for transportation, aviation, maritime, and military use.

Key Points

- Wireless operations permit services, such as long-range communications, that are impossible or impractical to implement with the use of wires.
- The most common wireless technologies use electromagnetic wireless telecommunications, such as radio.
- Less common methods of achieving wireless communications include the use of light, sound, magnetic, or electric fields.

Key Terms

- **radio wave**: Electromagnetic radiation having a wavelength between about.5 centimeters and 30,000 meters; used for the broadcasting of radio and television signals.
- **conductor**: A material which contains movable electric charges.
- **telecommunication**: The science and technology of the communication or messages over a distance, especially using electric, electronic or electromagnetic impulses.

CHAPTER OVERVIEW

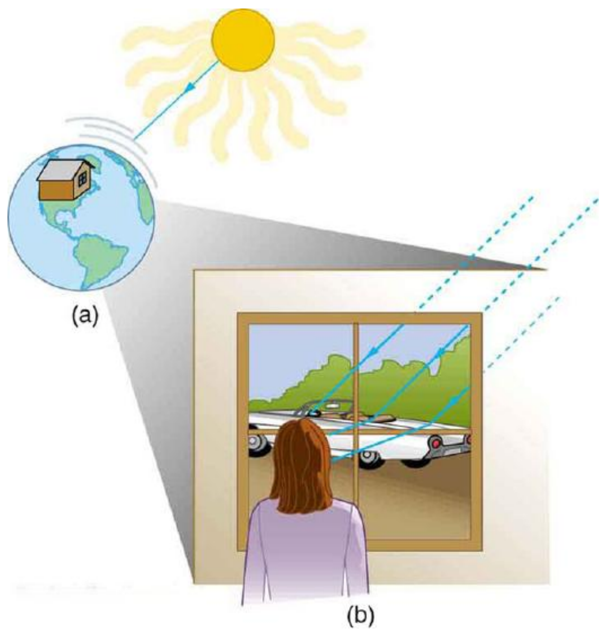
4: Geometric Optics

4.1: Overview

learning objectives

- Distinguish three ways that rays can travel

Rays, or beams of light, can travel in three ways: directly, through a material, or indirectly (reflection). These three methods of light travel are shown in this image. The word ray comes from mathematics, and refers to a straight line that originates at some point. Even when passing through a material, or bouncing off of a material in a reflection, the light continues to travel in a straight line, even if that line has changed direction. The movement of light, as a ray, can be shown with simple geometry and trigonometry. This is called geometric optics.



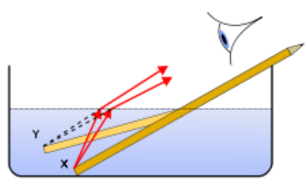
Methods of Travel by a Ray of Light: Light can travel through empty space directly from the source, through media like air and glass, reflect from an object like a mirror, or travel in a straight line.

Direct Light Travel

Direct light travel is when a ray of light starts at a source, and continues to travel from that source to its destination without encountering any interference. The light will continue in a straight line or ray until it reaches the observer. An example of this is the light that travels from the sun to the earth.

Light Travel Through a Material

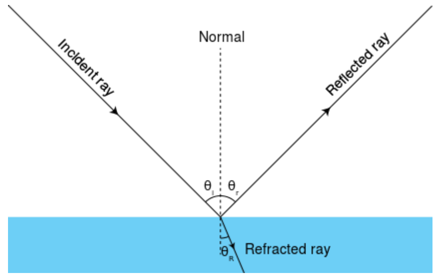
When light travels through any material, air, glass, water, etc., it encounters interference and changes direction. This is only a directional change and will continue in this new path, but still as a straight line, or ray. The law that deals with this change in direction is called the law of refraction. This change in ray direction will depend on the refractive index of the material through which the light is travelling. This concept is what led to the development of lenses and glasses. Have you ever noticed that if you put part of a pencil, spoon, or straw in a bowl of water, the object no longer appears straight, but seems to bend? This is because the index of refraction of the water is different from that of the air. This causes the light rays to change direction.



Refraction of Light Rays: The concept of refraction explains how a pencil submerged in water appears to bend.

Light Bouncing Off a Material

When light is bounced off of a material, such as a mirror, this is called a reflection. This is when a light ray, the incident ray, hits a reflective material and bounces off as the reflected ray at a specific angle. This is called the angle of reflection. Since the movement of the light rays can be shown geometrically, if a mirror is one-half your height, you could see your whole body in the reflection.



Reflected Rays: This diagram shows how light rays reflects off of a surface.

Key Points

- Direct light motion is when a ray of light travels from a source and is uninterrupted until it reaches it destination.
- Refracted light is when a light ray travels through another medium and, due to the difference in refractive indexes of the materials, changes direction slightly.
- When a light ray hits a reflective material, it bounces off as a reflected ray at a specific angle.

Key Terms

- **refraction**: Changing of a light ray's direction when it passes through variations in matter.
- **geometric optics**: Optics that describes light propagation in terms of "rays".
- **reflection**: the property of a propagated wave being thrown back from a surface (such as a mirror)

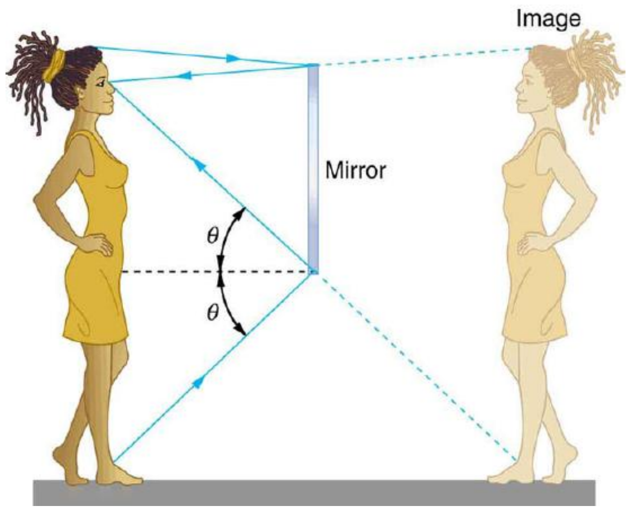
4.2: Reflection, Refraction, and Dispersion

learning objectives

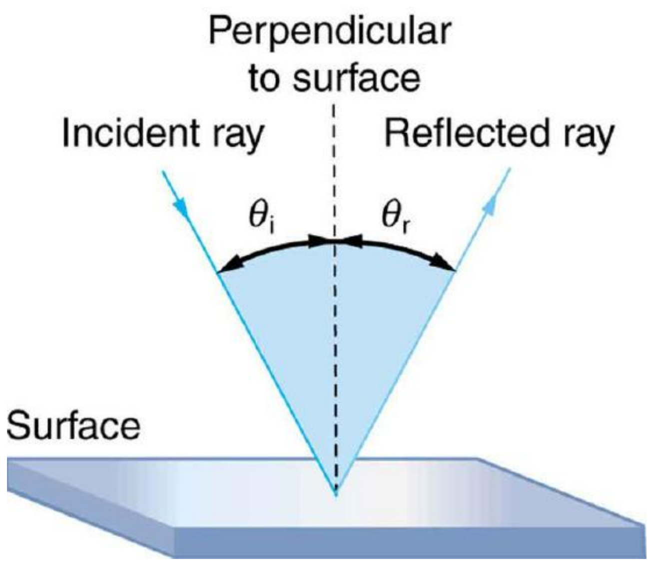
- Formulate the relationship between the angle of reflection and the angle of incidence

Whenever you look into a mirror or squint at sunlight glinting off a lake, you are seeing a reflection. When you look at the text in a book, you are actually seeing the light that is reflected from it. Large telescopes use reflections to form images of stars and other astronomical objects. In fact, the only way we can see an object that does not itself emit light is if that object reflects light.

The law of reflection is illustrated in, which also shows how the angles are measured relative to the perpendicular to the surface at the point where the light ray strikes. The law of reflection is very simple: The angle of reflection equals the angle of incidence. When we see our reflection in a mirror, it appears that our image is actually behind the mirror — we see the light coming from a direction determined by the law of reflection. The angles are such that our image appears exactly the same distance behind the mirror as we stand away from the mirror.

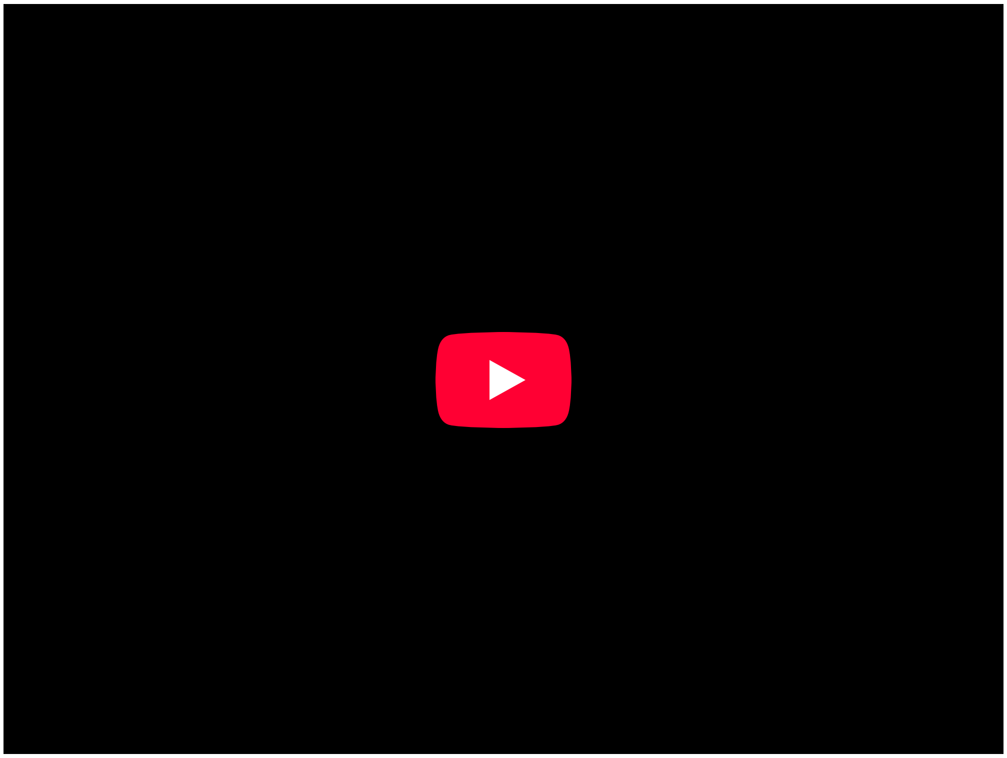


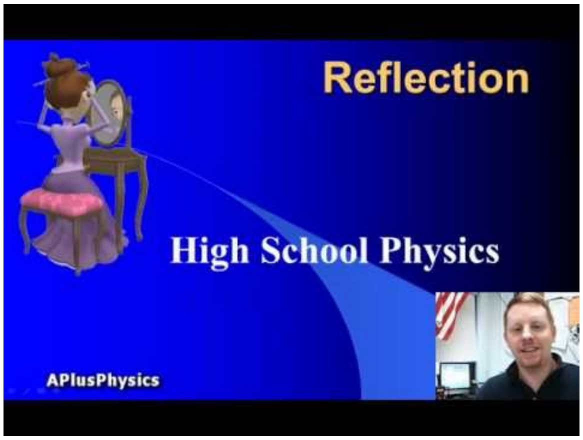
Mirror Reflection: An image in a mirror appears as though it is behind the mirror. The two rays shown are those that strike the mirror at just the correct angles to be reflected into the eyes of the viewer. The image appears to come from the direction the rays are coming from when they enter the viewer's eyes.



Law of Reflection: The law of reflection states that the angle of reflection equals the angle of incidence: θr = θi. The angles are measured relative to the perpendicular to the surface at the point where the ray strikes the surface.

We expect to see reflections off a smooth surface. However, light strikes different parts of a rough surface at different angles, and it is reflected in many different directions ("diffused"). Diffused light is what allows us to see a sheet of paper from any angle. Many objects, such as people, clothing, leaves, and walls, have rough surfaces and can be seen from all sides. A mirror, on the other hand, has a smooth surface (compared with the wavelength of light) and reflects light at specific angles. When the moon reflects off the surface of a lake, a combination of these effects takes place.





Reflection: A brief overview of reflection and the law of reflection.

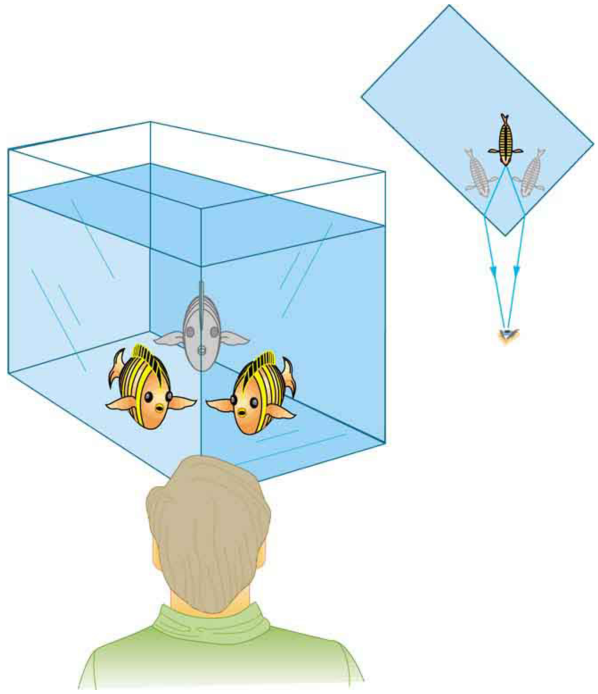
The Law of Refraction: Snell's Law and the Index of Refraction

The amount that a light ray changes its direction depends both on the incident angle and the amount that the speed changes.

learning objectives

- Formulate the relationship between the index of refraction and the speed of light

It is easy to notice some odd things when looking into a fish tank. For example, you may see the same fish appearing to be in two different places. This is because light coming from the fish to us changes direction when it leaves the tank, and in this case, it can travel two different paths to get to our eyes. The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction. Refraction is responsible for a tremendous range of optical phenomena, from the action of lenses to voice transmission through optical fibers.



Law of Refraction: Looking at the fish tank as shown, we can see the same fish in two different locations, because light changes directions when it passes from water to air. In this case, the light can reach the observer by two different paths, and so the fish seems to be in two different places. This bending of light is called refraction and is responsible for many optical phenomena.

Refraction: The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction.

Speed of Light

The speed of light c not only affects refraction, it is one of the central concepts of Einstein's theory of relativity. The speed of light varies in a precise manner with the material it traverses. It makes connections between space and time and alters our expectations that all observers measure the same time for the same event, for example. The speed of light is so important that its value in a vacuum is one of the most fundamental constants in nature as well as being one of the four fundamental SI units.

Why does light change direction when passing from one material (medium) to another? It is because light changes speed when going from one material to another.

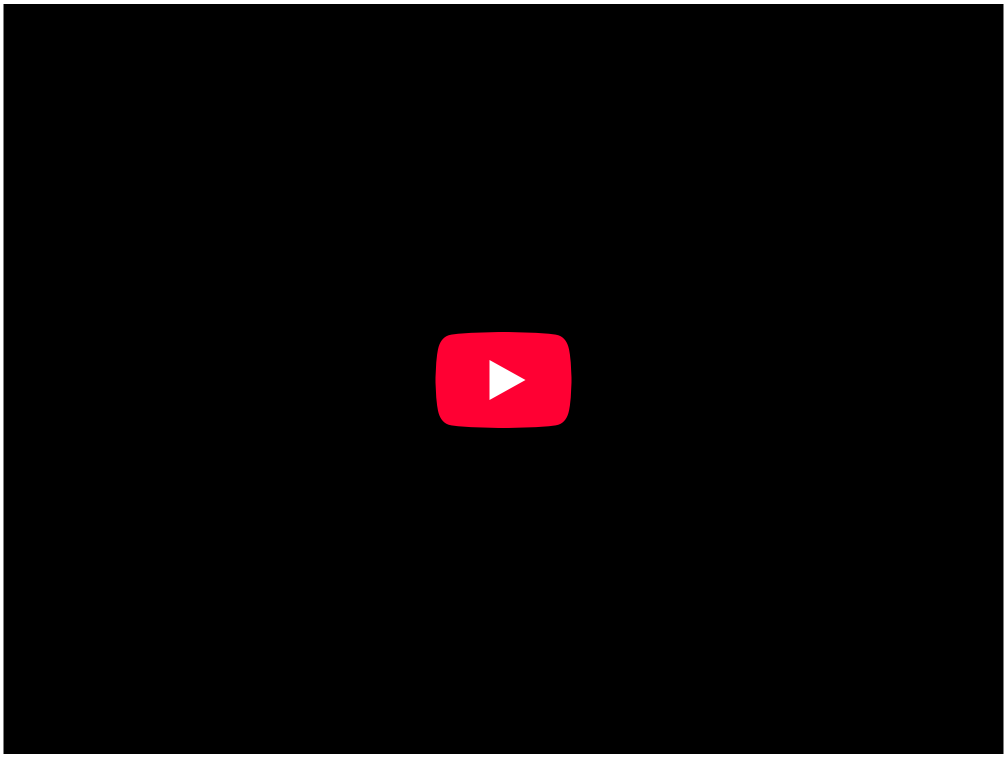
Law of Refraction

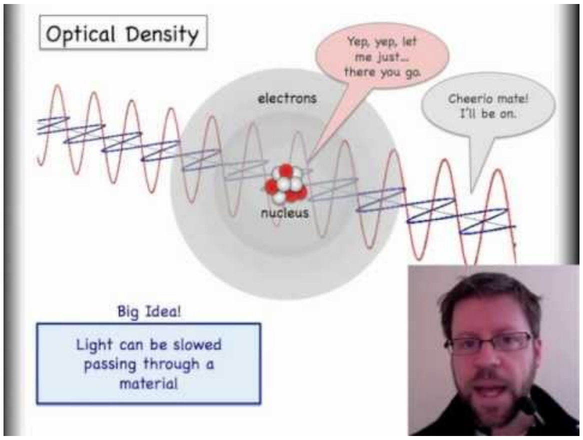
A ray of light changes direction when it passes from one medium to another. As before, the angles are measured relative to a perpendicular to the surface at the point where the light ray crosses it. The change in direction of the light ray depends on how the speed of light changes. The change in the speed of light is related to the indices of refraction of the media involved. In mediums that have a greater index of refraction the speed of light is less. Imagine moving your hand through the air and then moving it through a body of water. It is more difficult to move your hand through the water, and thus your hand slows down if you are applying the same amount of force. Similarly, light travels slower when moving through mediums that have higher indices of refraction.

The amount that a light ray changes its direction depends both on the incident angle and the amount that the speed changes. For a ray at a given incident angle, a large change in speed causes a large change in direction, and thus a large change in angle. The exact mathematical relationship is the law of refraction, or "Snell's Law," which stated in equation form as:

$$\mathrm{n}_1 \sin \theta_1 = \mathrm{n}_2 \sin \theta_2 \tag{4.2.1}$$

Here n_1 and n_2 are the indices of refraction for medium 1 and 2, and θ_1 and $\theta_2$are the angles between the rays and the perpendicular in medium 1 and 2. The incoming ray is called the incident ray and the outgoing ray the refracted ray, and the associated angles the incident angle and the refracted angle. The law of refraction is also called Snell's law after the Dutch mathematician Willebrord Snell, who discovered it in 1621. Snell's experiments showed that the law of refraction was obeyed and that a characteristic index of refraction n could be assigned to a given medium.





Understanding Snell's Law with the Index of Refraction: This video introduces refraction with Snell's Law and the index of refraction.The second video discusses total internal reflection (TIR) in detail. http://www.youtube.com/watch?v=fvrvqm3Erzk

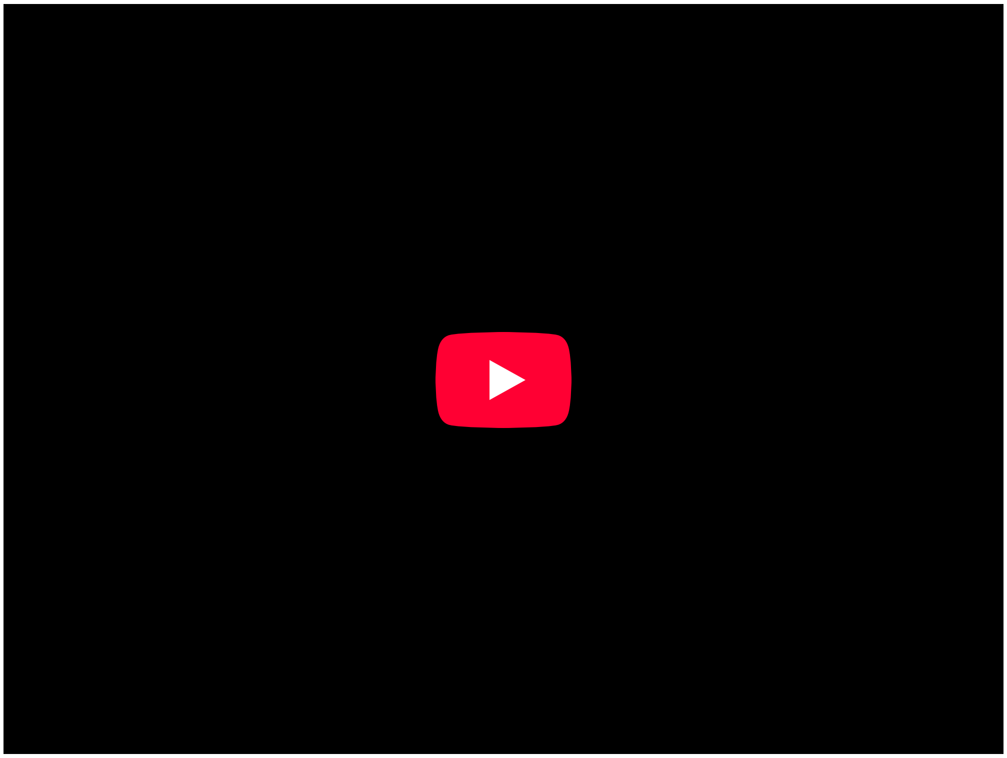
Total Internal Reflection and Fiber Optics

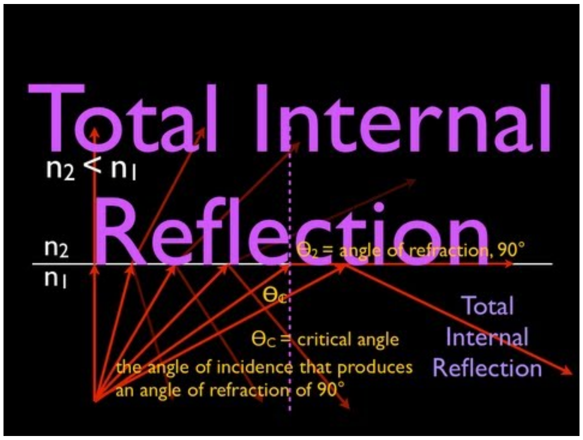
Total internal reflection happens when a propagating wave strikes a medium boundary at an angle larger than a particular critical angle.

learning objectives

- Formulate conditions required for the total internal reflection

Total internal reflection is a phenomenon that happens when a propagating wave strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected. The critical angle is the angle of incidence above which the total internal reflectance occurs.





What is Total Internal Reflection?: Describes the concept of total internal reflection, derives the equation for the critical angle and shows one example.

Critical angle

The critical angle is the angle of incidence above which total internal reflection occurs. The angle of incidence is measured with respect to the normal at the refractive boundary (see diagram illustrating Snell's law). Consider a light ray passing from glass into air. The light emanating from the interface is bent towards the glass. When the incident angle is increased sufficiently, the transmitted angle (in air) reaches 90 degrees. It is at this point no light is transmitted into air. The critical angle $\theta c\theta c$ is given by Snell's law, $n1\sin\theta1=n2\sin\theta2n1\sin\theta1=n2\sin\theta2$. Here, n_1 and n_2 are refractive indices of the media, and $\theta1\theta1$ and $\theta2\theta2$are angles of incidence and refraction, respectively. To find the critical angle, we find the value for $\theta1\theta1$ when $\theta2\theta2= 90°$ and thus $\sin\theta2=1\sin\theta2=1$. The resulting value of $\theta1\theta1$ is equal to the critical angle $\theta c=\theta1=\arcsin(n2n1)\theta c=\theta1=\arcsin(n2n1)$. So the critical angle is only defined when n_2/n_1 is less than 1.

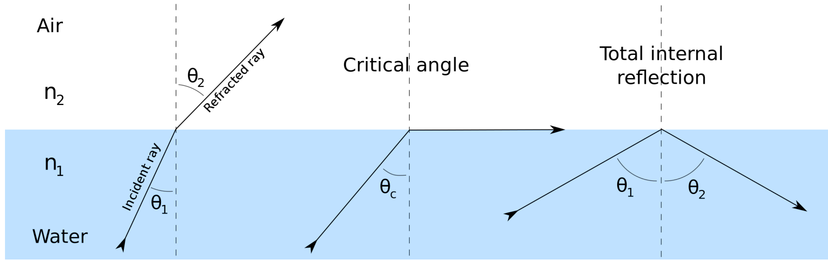


Fig 1: Refraction of light at the interface between two media, including total internal reflection.

Optical Fiber

Total internal reflection is a powerful tool since it can be used to confine light. One of the most common applications of total internal reflection is in fibre optics. An optical fibre is a thin, transparent fibre, usually made of glass or plastic, for transmitting light. The construction of a single optical fibre is shown in.

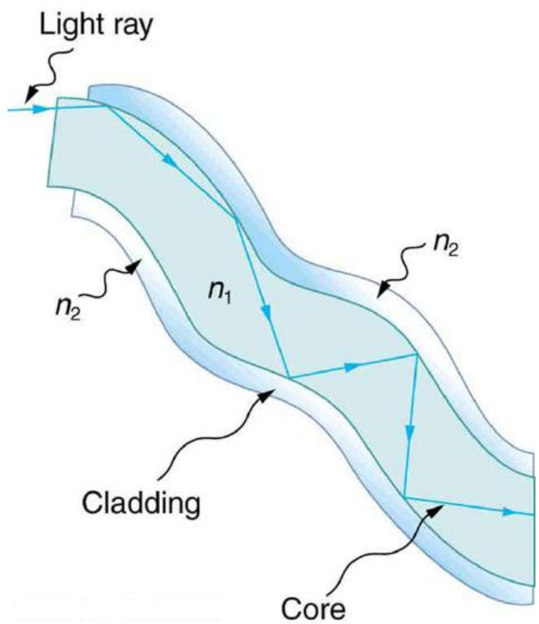


Fig 2: Fibers in bundles are clad by a material that has a lower index of refraction than the core to ensure total internal reflection, even when fibers are in contact with one another. This shows a single fiber with its cladding.

The basic functional structure of an optical fiber consists of an outer protective cladding and an inner core through which light pulses travel. The overall diameter of the fiber is about 125 μm and that of the core is just about 50 μm. The difference in refractive index of the cladding and the core allows total internal reflection in the same way as happens at an air-water surface show in. If light is incident on a cable end with an angle of incidence greater than the critical angle then the light will remain trapped inside the glass strand. In this way, light travels very quickly down the length of the cable over a very long distance (tens of kilometers). Optical fibers are commonly used in telecommunications, because information can be transported over long distances, with minimal loss of data. Another common use can be found in medicine in endoscopes. The field of applied science and engineering concerned with the design and application of optical fibers are called fiber optics.

Total Polarization

Brewster's angle is an angle of incidence at which light with a particular polarization is perfectly transmitted through a surface.

learning objectives

- Calculate the Brewster's angle from the indices of refraction and discuss its physical mechanism

Brewster's angle (also known as the polarization angle) is an angle of incidence at which light with a particular polarization is perfectly transmitted through a transparent dielectric surface, with no reflection. When unpolarized light is incident at this angle, the light that is reflected from the surface is therefore perfectly polarized. This special angle of incidence is named after the Scottish physicist Sir David Brewster (1781–1868).

The physical mechanism for this can be qualitatively understood from the manner in which electric dipoles in the media respond to p-polarized light (whose electric field is polarized in the same plane as the incident ray and the surface normal). One can imagine that light incident on the surface is absorbed, and then re-radiated by oscillating electric dipoles at the interface between the two media. The refracted light is emitted perpendicular to the direction of the dipole moment; no energy can be radiated in the direction of the dipole moment. Thus, if the angle of reflection θ_1 (angle of reflection) is equal to the alignment of the dipoles (90 – θ_2), where θ_2 is angle of refraction, no light is reflected.

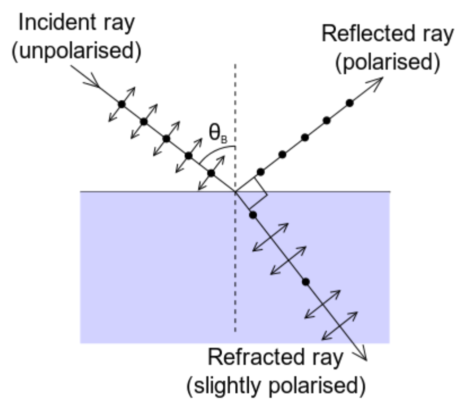
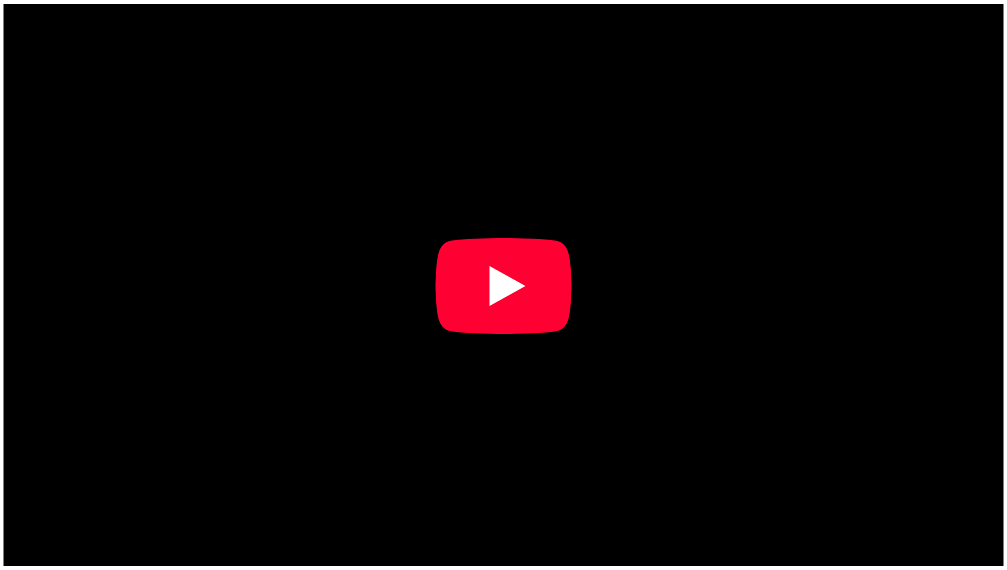


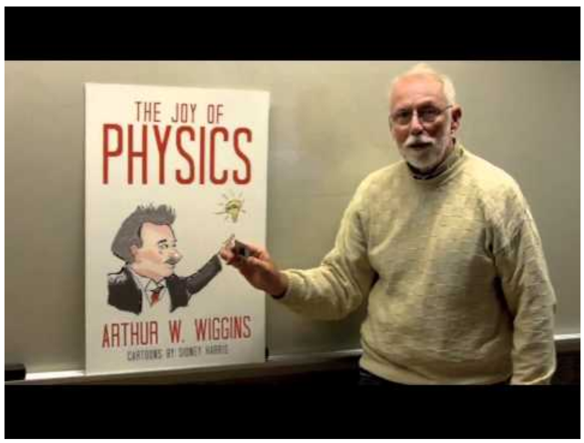
Fig 1: An illustration of the polarization of light that is incident on an interface at Brewster's angle.

This geometric condition can be expressed as $\theta_1 + \theta_2 = 90^\circ$, where θ_1 is the angle of incidence and θ_2 is the angle of refraction. Using Snell's law ($n_1\sin\theta 1$ = $n_2\sin\theta_2$), one can calculate the incident angle θ_1 = $_B$ at which no light is reflected: $\mathrm{n}_1 \sin(\theta_\mathrm{B}) = \mathrm{n}_2 \sin(90^\circ - \theta_\mathrm{B})$ Solving for θ_B gives $\theta_\mathrm{B} = \arctan\left(\frac{\mathrm{n}_2}{\mathrm{n}_1}\right)$.

When light hits a surface at a Brewster angle, reflected beam is linearly polarized. shows an example, where the reflected beam was nearly perfectly polarized and hence, blocked by a polarizer on the right picture. Polarized sunglasses use the same principle to reduce glare from the sun reflecting off horizontal surfaces such as water or road.

Fig 2: Photograph taken of a window with a camera polarizer filter rotated to two different angles. In the picture at left, the polarizer is aligned with the polarization angle of the window reflection. In the picture at right, the polarizer has been rotated 90° eliminating the heavily polarized reflected sunlight.





Polarization Experience: A polarizing filter allows light of a particular plane of polarization to pass, but scatters the rest of the light. When two polarizing filters are crossed, almost no light gets through. Some materials have molecules that rotate the plane of polarization of light. When one of these materials is placed between crossed polarizing filters, more light is allowed to pass through.

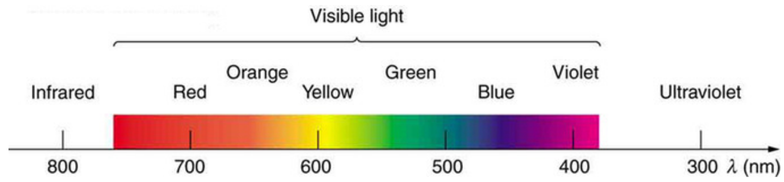
Dispersion: Rainbows and Prisims

Dispersion is defined as the spreading of white light into its full spectrum of wavelengths.

learning objectives

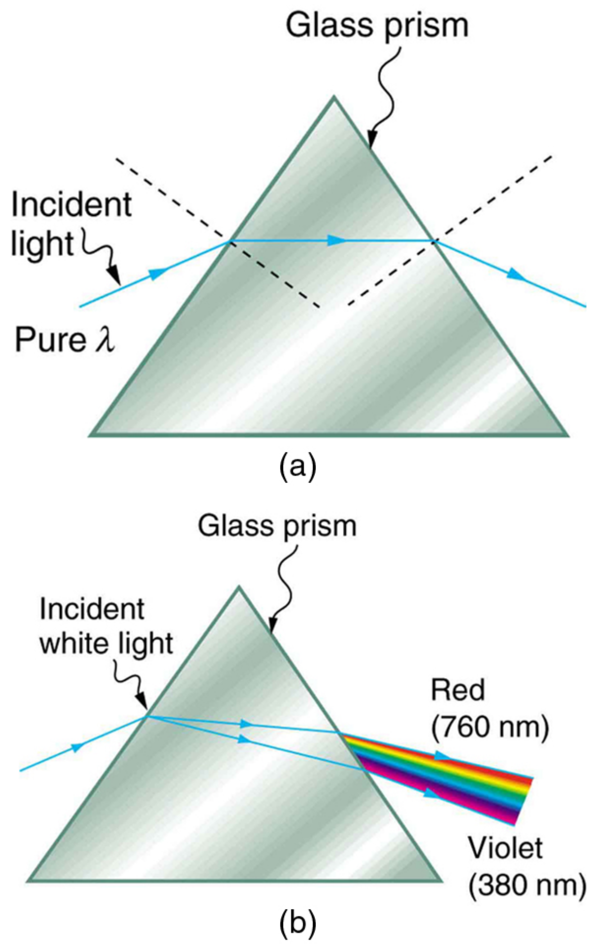
- Describe production of rainbows by a combination of refraction and reflection processes

We see about six colors in a rainbow—red, orange, yellow, green, blue, and violet; sometimes indigo is listed, too. These colors are associated with different wavelengths of light. White light, in particular, is a fairly uniform mixture of all visible wavelengths. Sunlight, considered to be white, actually appears to be a bit yellow because of its mixture of wavelengths, but it does contain all visible wavelengths. The sequence of colors in rainbows is the same sequence as the colors plotted versus wavelength. What this implies is that white light is spread out according to wavelength in a rainbow. Dispersion is defined as the spreading of white light into its full spectrum of wavelengths. More technically, dispersion occurs whenever there is a process that changes the direction of light in a manner that depends on wavelength. Dispersion, as a general phenomenon, can occur for any type of wave and always involves wavelength-dependent processes.



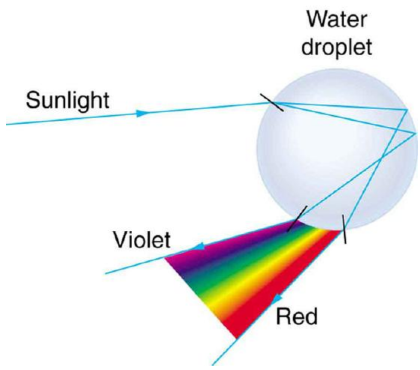
Colors of a Rainbow: Even though rainbows are associated with seven colors, the rainbow is a continuous distribution of colors according to wavelengths.

Refraction is responsible for dispersion in rainbows and many other situations. The angle of refraction depends on the index of refraction, as we saw in the Law of Refraction. We know that the index of refraction n depends on the medium. But for a given medium, n also depends on wavelength. Note that, for a given medium, n increases as wavelength decreases and is greatest for violet light. Thus violet light is bent more than red light and the light is dispersed into the same sequence of wavelengths.



Pure Light and Light Dispersion: (a) A pure wavelength of light falls onto a prism and is refracted at both surfaces. (b) White light is dispersed by the prism (shown exaggerated). Since the index of refraction varies with wavelength, the angles of refraction vary with wavelength. A sequence of red to violet is produced, because the index of refraction increases steadily with decreasing wavelength.

Rainbows are produced by a combination of refraction and reflection. You may have noticed that you see a rainbow only when you look away from the sun. Light enters a drop of water and is reflected from the back of the drop. The light is refracted both as it enters and as it leaves the drop. Since the index of refraction of water varies with wavelength, the light is dispersed, and a rainbow is observed. (There is no dispersion caused by reflection at the back surface, since the law of reflection does not depend on wavelength.) The actual rainbow of colors seen by an observer depends on the myriad of rays being refracted and reflected toward the observer's eyes from numerous drops of water. The arc of a rainbow comes from the need to be looking at a specific angle relative to the direction of the sun.



Light Reflecting on Water Droplet: Part of the light falling on this water drop enters and is reflected from the back of the drop. This light is refracted and dispersed both as it enters and as it leaves the drop.

Key Points

- Light strikes different parts of a rough surface at different angles and is reflected, or diffused, in many different directions.
- A mirror has a smooth surface (compared with the wavelength of light) and so reflects light at specific angles.
- We see the light reflected off a mirror coming from a direction determined by the law of reflection.
- The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction.
- The index of refraction is n=c/v, where v is the speed of light in the material, c is the speed of light in vacuum, and n is the index of refraction.
- Snell's law, the law of refraction, is stated in equation form as n1sinθ1=n2sinθ2n1sinθ1=n2sinθ2.
- The critical angle is the angle of incidence above which total internal reflection occurs and given as θc=arcsin(n2n1)θc=arcsin(n2n1).
- The critical angle is only defined when n2/n1 is less than 1.
- If light is incident on an optical fiber with an angle of incidence greater than the critical angle then the light will remain trapped inside the glass strand. Light can travel over a very long distance without a significant loss.
- When light hits a surface at a Brewster angle, reflected beam is linearly polarized.
- The physical mechanism for the Brewster's angle can be qualitatively understood from the manner in which electric dipoles in the media respond to p-polarized light.
- Brewsters' angle is given as θB=arctan(n2n1)θB=arctan(n2n1).
- Dispersion occurs whenever there is a process that changes the direction of light in a manner that depends on wavelength. Dispersion can occur for any type of wave and always involves wavelength-dependent processes.
- For a given medium, n increases as wavelength decreases and is greatest for violet light. Thus violet light is bent more than red light, as can be seen with a prism.
- In a rainbow, light enters a drop of water and is reflected from the back of the drop. The light is refracted both as it enters and as it leaves the drop.

Key Terms

- **reflection**: the property of a propagated wave being thrown back from a surface (such as a mirror)
- **refraction**: Changing of a light ray's direction when it passes through variations in matter.
- **index of refraction**: For a material, the ratio of the speed of light in vacuum to that in the material.
- **Snell's law**: A formula used to describe the relationship between the angles of incidence and refraction.
- **cladding**: One or more layers of materials of lower refractive index, in intimate contact with a core material of higher refractive index.
- **dipole**: A separation of positive and negative charges.
- **dielectric**: An electrically insulating or nonconducting material considered for its electric susceptibility (i.e., its property of polarization when exposed to an external electric field).
- **polarizer**: An optical filter that passes light of a specific polarization and blocks waves of other polarizations.

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4.3: Lenses

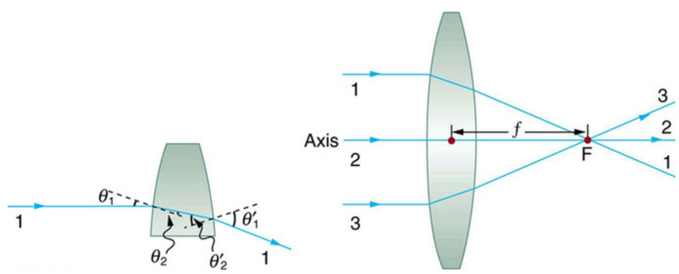
learning objectives

- Describe properties of a thin lens and the purpose of ray tracing

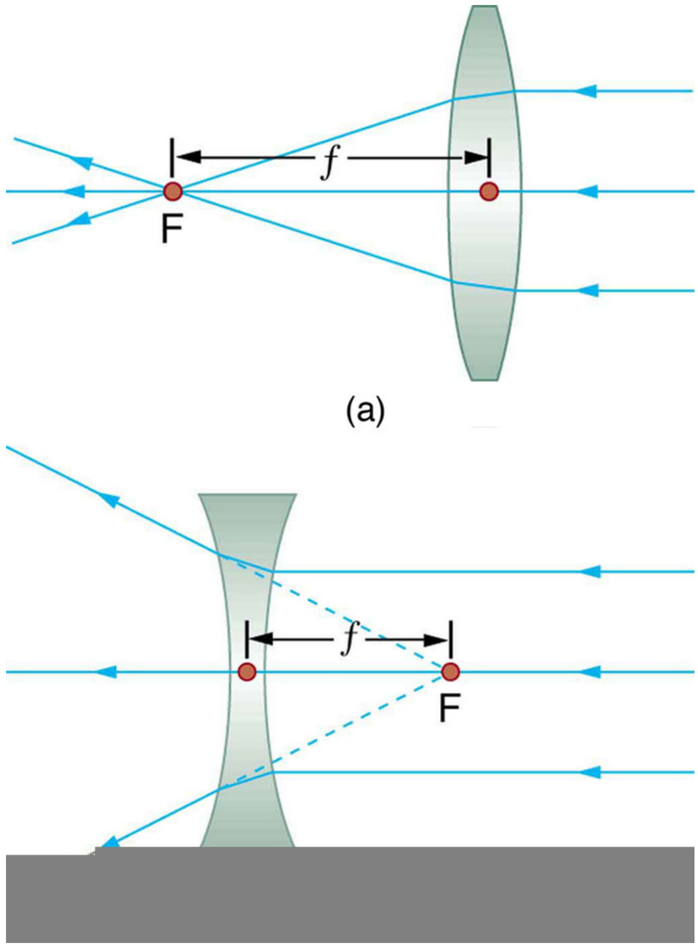
Thin Lenses and Ray Tracing

Ray tracing is the technique of determining or following (tracing) the paths that light rays take. Experiments, as well as our own experiences, show that when light interacts with objects several times as large as its wavelength, it travels in straight lines and acts like a ray. (A ray is simply a straight line that originates at a point.) Its wave characteristics are not pronounced in such situations. Since the wavelength of light is less than a micron (a thousandth of a millimeter), it acts like a ray in the many common situations in which it encounters objects larger than a micron, such as lenses.

For rays passing through matter, the law of refraction is used to trace the paths. Here we use ray tracing to help us understand the action of lenses in situations ranging from forming images on film to magnifying small print to correcting nearsightedness. While ray tracing for complicated lenses, such as those found in sophisticated cameras, may require computer techniques, there is a set of simple rules for tracing rays through thin lenses. A thin lens is defined to be one whose thickness allows rays to refract, as illustrated in, but does not allow properties such as dispersion and aberrations. An ideal thin lens has two refracting surfaces but the lens is thin enough toassume that light rays bend only once. Another way of saying this is that the lens thickness is much much smaller than the focal length of the lens. A thin symmetrical lens has two focal points, one on either side and both at the same distance from the lens. (See.) Another important characteristic of a thin lens is that light rays through its center are deflected by a negligible amount, as seen in the center rays in the first two figures. The treatment of a lens as a thin lens is known as the “thin lens approximation. ”



Convex Lens: Rays of light entering a converging lens parallel to its axis converge at its focal point F. (Ray 2 lies on the axis of the lens.) The distance from the center of the lens to the focal point is the lens’s focal length f. An expanded view of the path taken by ray 1 shows the perpendiculars and the angles of incidence and refraction at both surfaces.

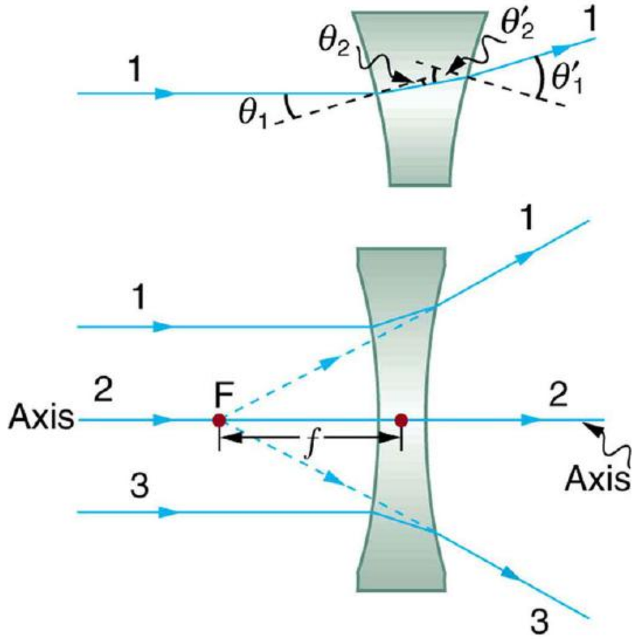


Thin Lens: Thin lenses have the same focal length on either side. (a) Parallel light rays entering a converging lens from the right cross at its focal point on the left. (b) Parallel light rays entering a diverging lens from the right seem to come from the focal point on the right.

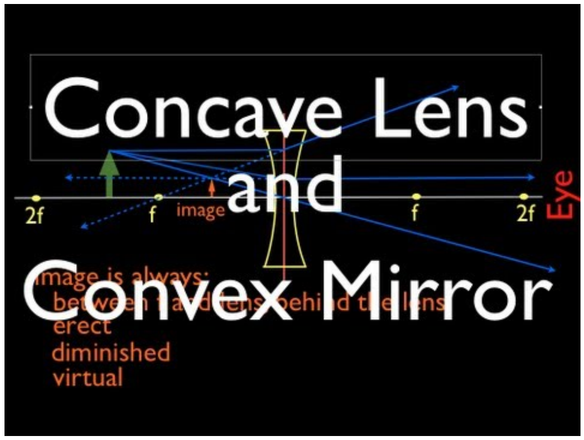
Rules for Ray Tracing

Using paper, pencil, and a straight edge, ray tracing can accurately describe the operation of a lens. The rules for ray tracing for thin lenses are based on the illustrations included in this section:

1. A ray entering a converging lens parallel to its axis passes through the focal point F of the lens on the other side. (See rays 1 and 3 in.)
2. A ray entering a diverging lens parallel to its axis seems to come from the focal point F. (See rays 1 and 3 in.)
3. A ray passing through the center of either a converging or a diverging lens does not change direction. (See ray 2 in and.)
4. A ray entering a converging lens through its focal point exits parallel to its axis. (The reverse of rays 1 and 3 in.)
5. A ray that enters a diverging lens by heading toward the focal point on the opposite side exits parallel to the axis. (The reverse of rays 1 and 3 in).



Diverging Lens: Rays of light entering a diverging lens parallel to its axis are diverged, and all appear to originate at its focal point F. The dashed lines are not rays—they indicate the directions from which the rays appear to come. The focal length f of a diverging lens is negative. An expanded view of the path taken by ray 1 shows the perpendiculars and the angles of incidence and refraction at both surfaces.



Ray Diagrams, Concave Lens and Convex Mirror: Shows how to draw the ray diagrams for locating the image produced by a concave lens and a convex mirror.

The Thin Lens Equation and Magnification

The thin lens equation relates the object distance d_o, image distance d_i, and focal length f.

learning objectives

- Formulate five basic rules of ray tracing

The Thin Lens Equation and Magnification

Image Formation by Thin Lenses

How does a lens form an image of an object? We can use the technique of ray tracing to illustrate how lenses form images. We can also develop equations to describe the images quantitatively. Recall the five basic rules of ray tracing:

1. A ray entering a converging lens parallel to its axis passes through the focal point F of the lens on the other side.
2. A ray entering a diverging lens parallel to its axis seems to come from the focal point F.
3. A ray passing through the center of either a converging or a diverging lens does not change direction.
4. A ray entering a converging lens through its focal point exits parallel to its axis.
5. A ray that enters a diverging lens by heading toward the focal point on the opposite side exits parallel to the axis.

Consider an object some distance away from a converging lens, as shown in. To find the location and size of the image formed, we trace the paths of selected light rays originating from one point on the object (in this case the top of the person's head). The figure shows three rays from the top of the object that can be traced using the five ray tracing rules. Rays leave this point going in many directions, but we concentrate on only a few with paths that are easy to trace. The first ray is one that enters the lens parallel to its axis and passes through the focal point on the other side (rule 1). The second ray passes through the center of the lens without changing direction (rule 3). The third ray passes through the nearer focal point on its way into the lens and leaves the lens parallel to its axis (rule 4). The three rays cross at the same point on the other side of the lens. The image of the top of the person's head is located at this point. All rays that come from the same point on the top of the person's head are refracted in such a way as to cross at the point shown. Rays from another point on the object, such as her belt buckle, will also cross at another common point, forming a complete image, as shown. Although three rays are traced in, only two are necessary to locate the image. It is best to trace rays for which there are simple ray tracing rules. Before applying ray tracing to other situations, let us consider the example shown in in more detail.

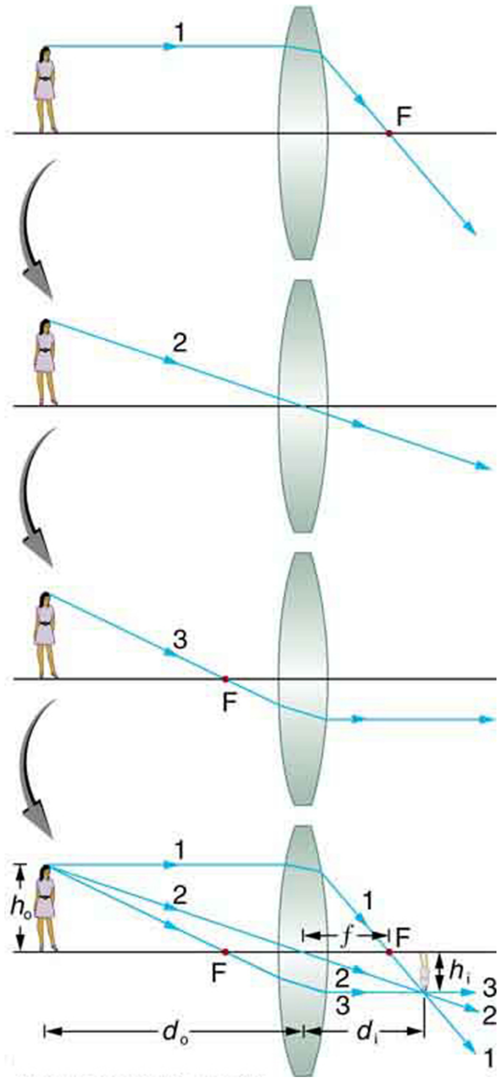


Image Formation with a Thin Lens: Ray tracing is used to locate the image formed by a lens. Rays originating from the same point on the object are traced—the three chosen rays each follow one of the rules for ray tracing, so that their paths are easy to determine. The image is located at the point where the rays cross. In this case, a real image—one that can be projected on a screen —is formed.

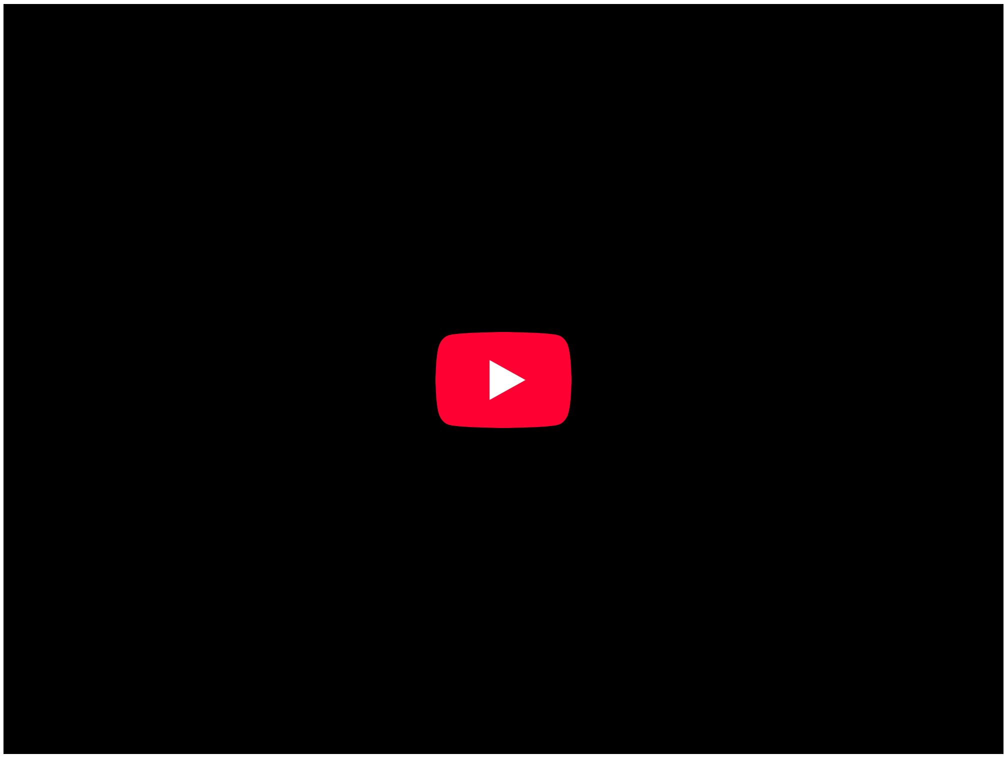
Several important distances appear in. We define d_o as the object distance—the distance of an object from the center of a lens. Image distance $d_i$is defined as the distance of the image from the center of a lens. The height of the object and height of the image are given the symbols h_o and h_i, respectively. Images that appear upright relative to the object have heights that are positive and those that are inverted have negative heights. Using the rules of ray tracing and making a scale drawing with paper and pencil, like that in, we can accurately describe the location and size of an image. But the real benefit of ray tracing is in visualizing how images are formed in a variety of situations. To obtain numerical information, we use a pair of equations that can be derived from a geometric analysis of ray tracing for thin lenses. The thin lens equation is:

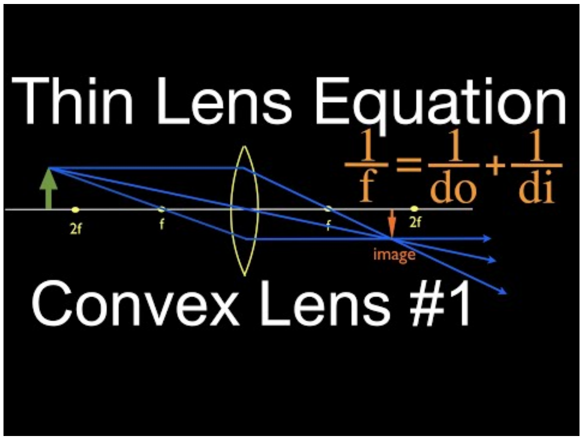
$$\frac{1}{\mathrm{d}_o}+\frac{1}{\mathrm{d_i}}=\frac{1}{\mathrm{f}} \tag{4.3.1}$$

We define the ratio of image height to object height (h_i/h_o) as the magnification m. The magnification is related to d_o, d_i, h_o, and h_i by the following relation:

$$\frac{\mathrm{h_i}}{\mathrm{h_o}}=-\frac{\mathrm{d_i}}{\mathrm{d_o}}=\mathrm{m} \tag{4.3.2}$$

In many cases both of these equations are referred to together as the thin lens equations. The thin lens equations are broadly applicable to all situations involving thin lenses (and “thin” mirrors).





Thin Lens Equations for a Convex Lens: Shows how to use the thin lens equation to calculate the image distance, image height and image orientation for convex lenses when the object distance is greater the the focal length (f).

Combinations of Lenses

A compound lens is an array of simple lenses with a common axis.

learning objectives

- Calculate focal length for a compound lens from the focal lengths of simple lenses

COMPOUND LENSES

In contrast to a simple lens, which consists of only one optical element, a compound lens is an array of simple lenses (elements) with a common axis. The use of multiple elements allows for the correction of more optical aberrations, such as the chromatic aberration caused by the wavelength-dependent index of refraction in glass, than is possible using a single lens. In many cases these aberrations can be compensated for to a great extent by using a combination of simple lenses with complementary aberrations.

The simplest case is where lenses are placed in contact: if the lenses of focal lengths f_1 and f_2 are “thin”, the combined focal length f of the lenses is given by

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2} \tag{4.3.3}$$

Since $1/f$ is the power of a lens, it can be seen that the powers of thin lenses in contact are additive.

If two thin lenses are separated in air by some distance d (where d is smaller than the focal length of the first lens), the focal length for the combined system is given by

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2} \tag{4.3.4}$$

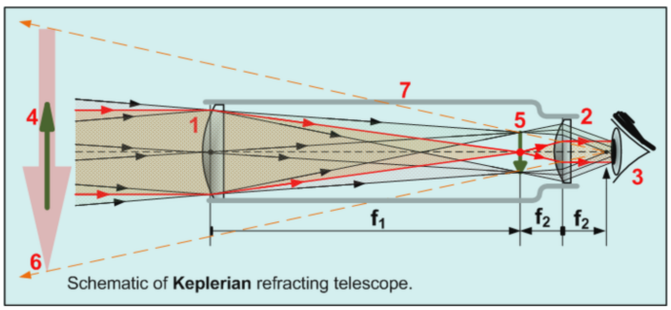
BACK FOCAL LENGTH

The distance from the second lens to the focal point of the combined lenses is called the *back focal length* (BFL).

$$\mathrm{BFL}=\frac{\mathrm{f}_2\left(\mathrm{d}-\mathrm{f}_1\right)}{\mathrm{d}-\left(\mathrm{f}_1+\mathrm{f}_2\right)} \tag{4.3.5}$$

As d tends to zero, the value of the BFL tends to the value of f given for thin lenses in contact.

If the separation distance is equal to the sum of the focal lengths ($d = f_1+f_2$), the combined focal length and BFL are infinite. This corresponds to a pair of lenses that transform a parallel (collimated) beam into another collimated beam (see). This type of system is called an afocal system, since it produces no net convergence or divergence of the beam. Two lenses at this separation form the simplest type of optical telescope. Although the system does not alter the divergence of a collimated beam, it does alter the width of the beam. The magnification of such a telescope is given by



Keplerian Telescope: All refracting telescopes use the same principles. The combination of an objective lens 1 and some type of eyepiece 2 is used to gather more light than the human eye could collect on its own, focus it 5, and present the viewer with a brighter, clearer, and magnified virtual image 6. The magnification can be found by dividing the focal length of the objective lens by the focal length of the eyepiece.

$$\mathrm{M}=-\frac{\mathrm{f}_2}{\mathrm{f}_1} \tag{4.3.6}$$

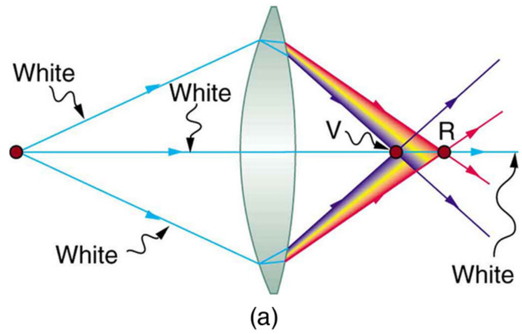
which is the ratio of the input beam width to the output beam width. Note the sign convention: a telescope with two convex lenses ($f_1 > 0$, $f_2 > 0$) produces a negative magnification, indicating an inverted image. A convex plus a concave lens ($f_1 > 0 > f_2$) produces a positive magnification and the image is upright.

ACHROMATS

An achromatic lens or achromat is a lens that is designed to limit the effects of chromatic and spherical aberration. Achromatic lenses are corrected to bring two wavelengths (typically red and blue/violet) into focus in the same plane.

The most common type of achromat is the achromatic doublet, which is composed of two individual lenses made from glasses with different amounts of dispersion Typically, one element is a negative (concave) element made out of flint, which has relatively high dispersion, and the other is a positive (convex) element made of crown glass, which has lower dispersion. The lens elements are mounted next to each other, often cemented together, and shaped so that the chromatic aberration of one is counterbalanced by that of the other.

In the most common type (shown in), the positive power of the crown lens element is not quite equaled by the negative power of the flint lens element. Together they form a weak positive lens that will bring two different wavelengths of light to a common focus. Negative doublets, in which the negative-power element predominates, are also made.



Achromatic Doublet: (a) Chromatic aberration is caused by the dependence of a lens's index of refraction on color (wavelength). The lens is more powerful for violet (V) than for red (R), producing images with different locations and magnifications. (b) Multiple-lens systems, such as this achromatic doublet, can partially correct chromatic aberrations, but they may require lenses of different materials and add to the expense of optical systems such as cameras.

The Lensmaker's Equation

The lensmaker's formula is used to relate the radii of curvature, the thickness, the refractive index, and the focal length of a thick lens.

learning objectives

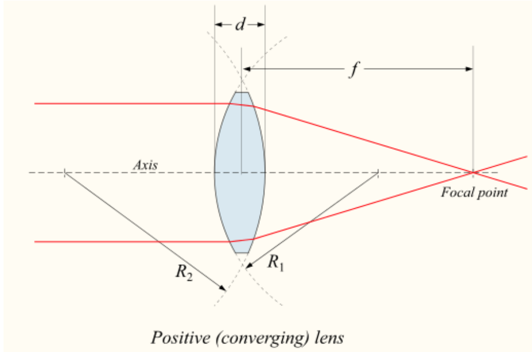
- Compare idealized thin lenses with real lenses

The Lensmaker's Equation

Thick Lenses

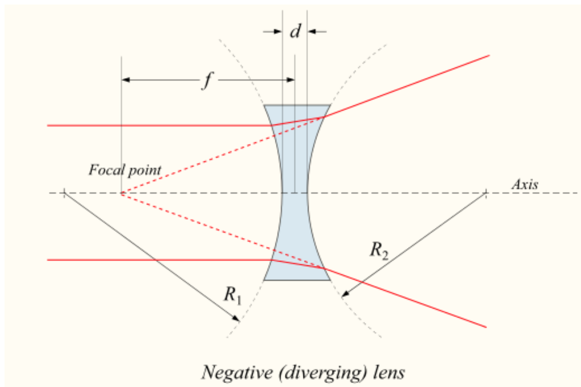
Unlike idealized thin lenses, real lenses have a finite thickness between their two surfaces of curvature. An ideal thin lens with two surfaces of equal curvature would have zero optical power, meaning that it would neither converge nor diverge light. A lens whose thickness is not negligible is called a thick lens. In this case, we can not simply assume that a light ray is only refracted once while traveling through the lens. Instead the extent of the refraction must be dependent on the thickness of the lens.

Lenses are classified by the curvature of the two optical surfaces. A lens is *biconvex* (or *double convex*, or just *convex*) if both surfaces are convex. If the lens is biconvex, a beam of light travelling parallel to the lens axis and passing through the lens will be converged (or *focused*) to a spot on the axis, at a certain distance behind the lens (i.e. the *focal length*). In this case, the lens is called a *positive* or *converging* lens. See for a diagram of a positive (converging) lens.



Thick Converging Lens: Diagram of a positive (converging) lens. The lensmaker's formula relates the radii of curvature, the index of refraction of the lens, the thickness of the lens, and the focal length.

If the lens is biconcave, a beam of light passing through the lens is diverged (spread); the lens is thus called a *negative* or *diverging* lens. The beam after passing through the lens appears to be emanating from a particular point on the axis in front of the lens; the distance from this point to the lens is also known as the focal length, although it is negative with respect to the focal length of a converging lens. See for a diagram of a negative (diverging) lens.



Negative Diverging Lens: Diagram of a negative (diverging) lens. The lensmaker's formula relates the radii of curvature, the index of refraction of the lens, the thickness of the lens, and the focal length.

The focal length of a thick lens *in air* can be calculated from the lensmaker's equation:

$$\mathrm{P}=\frac{1}{\mathrm{f}}=(\mathrm{n}-1)\left[\frac{1}{\mathrm{R}_1}-\frac{1}{\mathrm{R}_2}+\frac{(\mathrm{n}-1)\mathrm{d}}{\mathrm{n}\mathrm{R}_1\mathrm{R}_2}\right] \tag{4.3.7}$$

where

- P is the power of the lens,
- f is the focal length of the lens,
- n is the refractive index of the lens material,
- $R_1$is the radius of curvature of the lens surface closest to the light source,
- R_2 is the radius of curvature of the lens surface farthest from the light source, d and is the thickness of the lens (the distance along the lens axis between the two surface vertices).

Sign convention of Radii R_1 and R_2

The signs of the lens' radii of curvature indicate whether the corresponding surfaces are convex or concave. The sign convention used to represent this varies, but for our treatment if R_1 is positive the first surface is convex, and if R_1 is negative the surface is concave. The signs are reversed for the back surface of the lens: if R_2 is positive the surface is concave, and if R_2 is negative the surface is convex. If either radius is infinite, the corresponding surface is flat. With this convention the signs are determined by the shapes of the lens surfaces, and are independent of the direction in which light travels through the lens.

Thin Lens Approximation

The above equation can be greatly simplified if the lens thickness *d* is very small compared to R_1 and R_2. In this case, the thin lens approximation can then be made and the lensmaker's equation can be approximated as

$$P = \frac{1}{f} \approx (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right] \tag{4.3.8}$$

The focal length *f* is positive for converging lenses, and negative for diverging lenses. The reciprocal of the focal length, 1/*f*, is the optical of the lens. If the focal length is in meters, this gives the optical power in diopters (inverse meters).

Lenses have the same focal length when light travels from the back to the front as when light goes from the front to the back, although other properties of the lens, such as the aberrations are not necessarily the same in both directions.

Refraction Through Lenses

Because the index of refraction of a lens is greater than air, a ray moves towards the perpendicular as it enters and away as it leaves.

learning objectives

- Compare the effect of a convex lens and a concave lens on the light rays

Refraction Through Lenses

Lenses are found in a huge array of optical instruments, ranging from the simple magnifying glass to a camera lens to the lens of the human eye. The word *lens* derives from the Latin word for lentil bean—the shape of which is similar to that of the convex lens (as shown in). The convex lens is shaped so that all light rays that enter it parallel to its axis cross one another at a single point on the opposite side of the lens. The axis is defined as a line normal to the lens at its center (as shown in). Such a lens is called a converging (or convex) lens for the corresponding effect it has on light rays. The expanded view of the path of one ray through the lens illustrates how the ray changes direction both as it enters and as it leaves the lens.

Since the index of refraction of the lens is greater than that of air, the ray moves towards the perpendicular as it enters, and away from the perpendicular as it leaves (this is in accordance with the law of refraction). Due to the lens's shape, light is thus bent toward the axis at both surfaces. The point at which the rays cross is defined as the focal point F of the lens. The distance from the center of the lens to its focal point is defined as the focal length f of the lens. shows how a converging lens, such as that in a magnifying glass, can concentrate (converge) the nearly parallel light rays from the sun towards a small spot.

Magnifying Glass: Sunlight focused by a converging magnifying glass can burn paper. Light rays from the sun are nearly parallel and cross at the focal point of the lens. The more powerful the lens, the closer to the lens the rays will cross.

The greater effect a lens has on light rays, the more powerful it is said to be. For example, a powerful converging lens will focus parallel light rays closer to itself and will have a smaller focal length than a weak lens. The light will also focus into a smaller, more intense spot for a more powerful lens. The power P of a lens is defined as the inverse of its focal length. In equation form:

$$\mathrm{P}=\frac{1}{\mathrm{f}} \tag{4.3.9}$$

shows the effect of a concave lens on rays of light entering it parallel to its axis (the path taken by ray 2 in the figure is the axis of the lens). The concave lens is a *diverging lens,* because it causes the light rays to bend away (diverge) from its axis. In this case, the lens is shaped so that all light rays entering it parallel to its axis appear to originate from the same point F, defined as the focal point of a diverging lens. The distance from the center of the lens to the focal point is again called the focal length f of the lens. Note that the focal length and power of a diverging lens are defined as negative. For example, if the distance to F in is 5.00 cm, then the focal length is f=–5.00 cm and the power of the lens is P=–20 D. The expanded view of the path of one ray through the lens illustrates how the shape of the lens (given the law of refraction) causes the ray to follow its particular path and be diverged.

In subsequent sections we will examine the technique of ray tracing to describe the formation of images by lenses. Additionally, we will explore how image locations and characteristics can be quantified with the help of a set of geometric optics equations.

Key Points

- When light interacts with objects several times as large as its wavelength, it travels in straight lines and acts like a ray. A ray is simply a straight line that originates at a point.
- Ray tracing is the method for determining the paths light takes through matter, such as optical systems that include lenses.
- A thin lens is defined as one with a thickness that allows rays to refract, as illustrated in, but that does not allow properties such as dispersion and aberrations. An ideal thin lens has two refracting surfaces but the lens is thin enough to assume that light rays bend only once.
- There are five basic rules for tracing rays through a lens.
- Ray tracing can be used to construct an image from the light rays originating from an object that pass through a lens. The image is located at the point where the rays cross. By choosing several points from an object the entire image can be constructed.
- We define do to be the object distance, the distance of an object from the center of a lens. Image distance di is defined to be the distance of the image from the center of a lens. The height of the object and height of the image are given the symbols ho and hi, respectively.
- The thin lens equation quickly provides the relation between d_i, d_o, and the focal length f. It can be derived from a geometric analysis of ray tracing for thin lenses and is given by $\frac{1}{\mathrm{d_o}}+\frac{1}{\mathrm{d_i}}=\frac{1}{\mathrm{f}}$.
- The magnification m of an image is the ratio between the image and object height (h_i/h_o). The magnification is related to d_o, d_i, h_o, and h_i by the following relation: $\frac{\mathrm{h_i}}{\mathrm{h_o}}=-\frac{\mathrm{d_i}}{\mathrm{d_o}}=\mathrm{m}$.
- The use of multiple elements allows for the correction of more optical aberrations, such as the chromatic abberation caused by the wavelength -dependent index of refraction in glass, than is possible using a single lens.
- If the lenses of focal lengths f_1 and $f_2$are "thin", the combined focal length f of the lenses is given by $\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2}$ while if the lenses are separated by some distance d then the combined focal length is given by $\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2}$.
- If the separation distance is equal to the sum of the focal lengths ($d = f_1+f_2$), the combined focal length is infinite. This corresponds to a pair of lenses that transform a collimated beam into another collimated beam. This type of system is called an afocal system (a simple optical telescope).
- An achromatic doublet is a kind of compound lens designed to bring two wavelengths (typically red and blue/violet) into focus in the same plane. This (partially) corrects for the chromatic aberration found in a single simple lens. See.
- If a lens is biconvex, a beam of light travelling parallel to the lens axis and passing through the lens will be focused to a spot on the axis, at a certain distance behind the lens (i.e. the focal length). In this case, the lens is called a positive or converging lens. See.
- If a lens is biconcave, a beam of light passing through the lens is diverged (spread); the lens is thus called a negative or diverging lens. See.
- The focal length of a thick lens in air can be calculated from the lensmaker's equation: $\mathrm{P}=\frac{1}{\mathrm{f}}=(\mathrm{n}-1)\left[\frac{1}{\mathrm{R_1}}-\frac{1}{\mathrm{R_2}}+\frac{(\mathrm{n}-1)\mathrm{d}}{\mathrm{nR_1R_2}}\right]$.
- The signs of the lens' radii of curvature indicate whether the corresponding surfaces are convex or concave. The signs are reversed for the back surface of the lens: if R_2 is positive the surface is concave, and if R_2 is negative the surface is convex.
- The lensmaker's equation can be greatly simplified if the lens thickness d is very small compared to R_1 and R_2. In this case, the thin lens approximation can then be made and the lensmaker's equation can be approximated as $P=\frac{1}{f}\approx(n-1)\left[\frac{1}{R_1}-\frac{1}{R_2}\right]$.

- Recall that the a ray will bend as it enters a medium with a different refractive index. Since the refractive index of a lens is greater than air, a light ray will move towards the perpendicular as it enters and away as it leaves.
- A convex lens has been shaped so that all light rays that enter it parallel to its axis cross one another at a single point on the opposite side of the lens (the focal point). Such a lens is called a converging (or convex) lens for the converging effect it has on light rays. See.
- A concave lens is a diverging lens, because it causes the light rays to bend away (diverge) from its axis. shows the effect it has on rays of light that enter it parallel to its axis (the path taken by ray 2 in the figure is the axis of the lens).
- The greater effect a lens has on light rays, the more powerful it is said to be. A powerful converging lens will focus parallel light rays closer to itself and will have a smaller focal length than a weak lens. The power of a lens is given by the equation $\mathrm{P}=\frac{1}{\mathrm{f}}$.

Key Terms

- **focal point**: A focus—a point at which rays of light or other radiation converge.
- **ray tracing**: A technique used in optics for analysis of optical systems.
- **thin lens**: A thin lens is defined to be one whose thickness allows rays to refract but does not allow properties such as dispersion and aberrations.
- **thin lens equation**: Relates object distance do, image distance di, and focal length f: $\frac{1}{\mathrm{d_o}}+\frac{1}{\mathrm{d_i}}=\frac{1}{\mathrm{f}}$
- **image distance**: The distance of the image from the center of the lens.
- **magnification**: The apparent enlargement of an object in an image.
- **aberration**: The convergence to different foci, by a lens or mirror, of rays of light emanating from one and the same point, or the deviation of such rays from a single focus; a defect in a focusing mechanism that prevents the intended focal point.
- **afocal system**: An optical system that produces no net convergence or divergence of the beam, i.e. has an infinite effective focal length. This type of system can be created with a pair of optical elements where the distance between the elements is equal to the sum of each element's focal length (d = f1+f2).
- **achromatic doublet**: A type of lens made up of two simple lenses paired together designed so that the chromatic aberration of each lens partially offsets the other; in this way light in a range of wavelengths may be brought to the same focus.
- **thick lens**: Lenses whose thicknesses are not negligible (i.e., one cannot make the simple assumption that a light ray is refracted only once in the lens).
- **surface vertices**: The points where each surface crosses the optical axis. They are important primarily because they are the physically measurable parameters for the position of the optical elements, and so the positions of the other cardinal points must be known with respect to the vertices to describe the physical system.
- **convex lens**: A lens having at least one convex surface, such that light passing through it, may be brought to a focus.
- **concave lens**: A lens having at least one concave surface, such that light rays passing through it bend away from its optical axis.

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4.4: Mirrors

> **learning objectives**
>
> - Describe interaction of the light with a mirror surface

Plane Mirrors and Reflection

A mirror is a reflective surface that does not allow the passage of light and instead bounces it off, thus producing an image. The most common mirrors are flat and called plane mirrors. These mirrors are made by putting a thin layer of silver nitrate or aluminium behind a flat piece of glass.

When you place an object in front of a mirror, you see an image of the same object in the mirror. The object is the source of the incident rays, and the image is formed by the reflected rays. An image formed by reflection may be real or virtual. A "real" image occurs when light rays actually intersect at the image, and become inverted, or turned upside down. A "virtual" image occurs when light rays do not actually meet at the image. Instead, you "see" the image because your eye projects light rays backward. You are fooled into seeing an image! A virtual image is right side up (upright).

In flat, or plane mirrors, the image is a virtual image, and is the same distance behind the mirror as the object is in front of the mirror. The image is also the same size as the object. These images are also parity inverted, which means they have a left-right inversion.

Ray Diagrams

The way that we can predict how a reflection will look is by drawing a ray diagram. These diagrams can be used to find the position and size of the image and whether that image is real or virtual. These are the steps you follow to draw a ray diagram:

1. Draw the plane mirror as a straight line on a principal axis. The principal axis is an imaginary line that is drawn perpendicular to the mirror.
2. Draw the object as an arrow in front of the mirror.
3. Draw the image of the object, by using the principle that the image is placed at the same distance behind the mirror that the object is in front of the mirror. The image size is also the same as the object size. shows these first three steps.
4. Place a dot at the point the eye is located.
5. Pick one point on the image and draw the reflected ray that travels to the eye as it sees this point. Remember to add an arrowhead.
6. Draw the incident ray for light traveling from the corresponding point on the object to the mirror, such that the law of reflection is obeyed.
7. Continue for other extreme points on the object (i.e. the tip and base of the arrow). A completed ray diagram is shown in

The angle in which a light ray hits the mirror is the same angle in which it will be reflected back. If, for example, a light ray leaves the top of an object travelling parallel to the principal axis, it will hit the mirror at a 0 degree angle, and be reflected back at 0 degrees. When this happens, we say the ray hit the mirror normally. If the light ray hit the object at a 30 degree angle, it will be reflected back at a 30 degree angle.

Image Formation by Spherical Mirrors: Reflection and Sign Conventions

A mirror is a reflective surface that light does not pass through, made by a layer of silver nitrate or aluminium behind piece of glass.

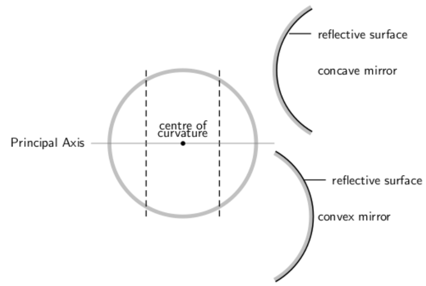
> **learning objectives**
>
> - Distinguish properties of the concave and the convex mirrors

Overview

A mirror is a reflective surface that light does not pass through, but bounces off of and this produces an image. Mirrors are made by putting a thin layer of silver nitrate or aluminium behind a flat piece of glass.

When you place an object in front of a mirror, you see the same object in the mirror. This image that appears to be behind the mirror is called the image. The object is the source of the incident rays, and the image is formed by the reflected rays. An image formed by reflection may be real or virtual. A real image occurs when light rays actually intersect at the image, and is inverted, or upside down. A virtual image occurs when light rays do not actually meet at the image. Instead, you “see” the image because your eye projects light rays backward. A virtual image is right side up (upright).

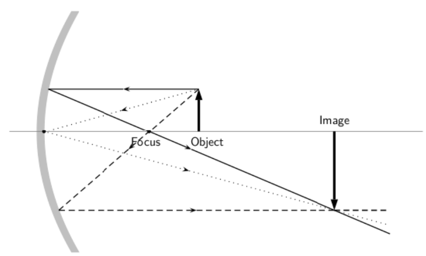
This section will cover spherical mirrors. Spherical mirrors can be either concave or convex. The center of curvature is the point at the center of the sphere and describes how big the sphere is. These concepts are shown in.



Spherical Mirrors: This figure shows the difference between a concave and convex mirror.

Concave Mirrors

In a concave mirror, the principal axis is a line that is perpendicular to the center of the mirror. The easiest way to visualize what a image will look like in this type of mirror is a ray diagram. Before that can be done, the focal point must first be defined. This point is half way between the mirror and the center of curvature on the principal axis. The distance to the focal point from the mirror is called the focal length. We can see from the figure that this focal length is also equal to half of the radius of the curvature. shows the ray diagram of a concave mirror.



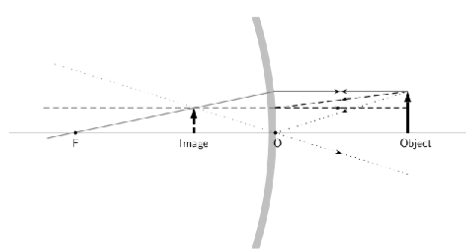
Concave Ray Diagram: This is a ray diagram of a concave mirror. The steps taken to draw are the same as those in a plane mirror.

A summary of the properties of concave mirrors is shown below:

- converging
- real image
- inverted
- image in front of mirror

Convex Mirrors

In convex mirrors, the principal axis is the same as in a plane or concave mirror, perpendicular to the center of the mirror. In this case, the focal point is behind the mirror. A convex mirror has a negative focal length because of this. The focal point is the same distance from the mirror as in a concave mirror. This is shown in.



Convex Mirror Ray Diagram: A convex mirror with three rays drawn to locate the image. Each incident ray is reflected according to the Law of Reflection. The reflected rays diverge. If the reflected rays are extended behind the mirror, then their intersection gives the location of the image behind the mirror. For a convex mirror, the image is virtual and upright.

A summary of the properties of convex mirrors is shown below:

- diverging
- virtual image
- upright
- image behind mirror

Key Points

- Reflected images can be either real or virtual. In a plane mirror, the images are virtual.
- The virtual images in a plane mirror have a left-right inversion.
- Drawing a ray diagram is a way to predict what a reflected image will look like.
- Images in mirrors can be either real or virtual.
- A summary of the properties of the concave mirrors are shown below: converging real image inverted image in front of mirror.
- A summary of the properties of the convex mirrors are shown below: diverging virtual image upright image behind mirror.

Key Terms

- **virtual image**: A virtual image occurs when light rays do not actually meet at the image
- **concave**: curved like the inner surface of a sphere or bowl
- **convex**: curved or bowed outward like the outside of a bowl or sphere or circle

CHAPTER OVERVIEW

5: Vision and Optical Instruments

Topic hierarchy

5.1: The Human Eye

learning objectives

- Identify parts of human eye and their functions

The human eye is the gateway to one of our five senses. The human eye is an organ that reacts with light. It allows light perception, color vision and depth perception. A normal human eye can see about 10 million different colors! There are many parts of a human eye, and that is what we are going to cover in this atom.

Properties

Contrary to what you might think, the human eye is not a perfect sphere, but is made up of two differently shaped pieces, the cornea and the sclera. These two parts are connected by a ring called the limbus. The part of the eye that is seen is the iris, which is the colorful part of the eye. In the middle of the iris is the pupil, the black dot that changes size. The cornea covers these elements, but is transparent. The fundus is on the opposite of the pupil, but inside the eye and can not be seen without special instruments. The optic nerve is what conveys the signals of the eye to the brain. is a diagram of the eye. The human eye is made up of three coats:

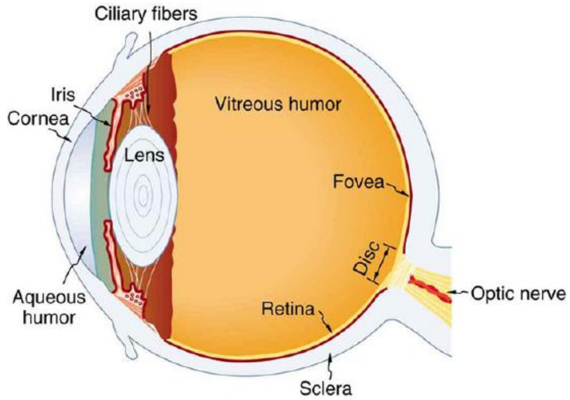


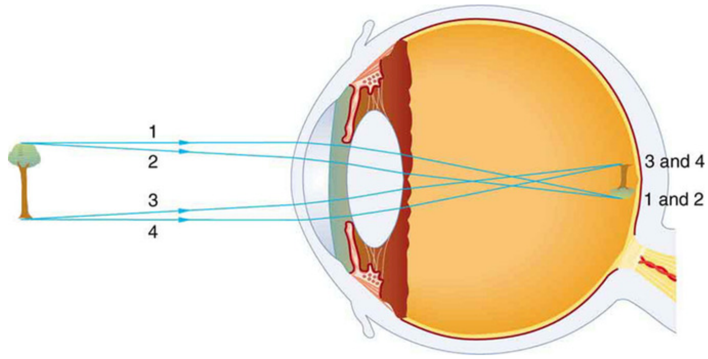
Diagram of the Human Eye: The cornea and lens of an eye act together to form a real image on the light-sensing retina, which has its densest concentration of receptors in the fovea and a blind spot over the optic nerve. The power of the lens of an eye is adjustable to provide an image on the retina for varying object distances. Layers of tissues with varying indices of refraction in the lens are shown here. However, they have been omitted from other pictures for clarity.

1. Outermost Layer – composed of the cornea and the sclera.
2. Middle Layer – composed of the choroid, ciliary body and iris.
3. Innermost Layer – the retina, which can be seen with an instrument called the ophthalmoscope.

Once you are inside these three layers, there is the aqueous humor (clear fluid that is contained in the anterior chamber and posterior chamber), vitreous body (clear jelly that is much bigger than the aqueous humor), and the flexible lens. All of these are connected by the pupil.

Dynamics

Whenever the eye moves, even just a little, it automatically readjusts the exposure by adjusting the iris, which regulates the size of the pupil. This is what helps the eye adjust to dark places or really bright lights. The lens of the eye is similar to one in glasses or cameras. The human eye is had an aperture, just like a camera. The pupil serves this function, and the iris is the aperture stop. The different parts of the eye has different refractive indexes, and this is what bends the rays to form an image. The cornea provides two-thirds of the power to the eye. The lens provides the remaining power. The image passes through several layers of the eye, but happens in a way very similar to that of a convex lens. When the image finally reaches the retena, it is inverted, but the brain will correct this. shows what happens.



Vision Diagram: An image is formed on the retina with light rays converging most at the cornea and upon entering and exiting the lens. Rays from the top and bottom of the object are traced and produce an inverted real image on the retina. The distance to the object is drawn smaller than scale.

Eye Movement

Each eye has six muscles; lateral rectus, medial rectus, inferior rectus, superior rectus, inferior oblique, and superior oblique. All of these muscles provide differnt tensions and torques to control the movement of the eye. These are a few examples of types of eye movement:

- Rapid Eye Movement – Often referred to as REM, this happens in the sleep stage when most vivid dreams occur.
- Saccade – These are quick, simultaneous movements of both eyes, and is controlled by the frontal lobe of the brain.
- Vestibulo-ocular Reflex – This is the eye movement which is opposite to the movement of the head and keeps the object you are looking at in the center of vision.
- Pursuit Movement – This is the tracking movement when you are following a moving object. It is less accurate than the vestibulo-ocular reflex.

Color Vision

Using the cone cells in the retina, we perceive images in color; each type of cone specifically sees in regions of red, green, or blue.

learning objectives

- Explain how the human eye perceives colors

With human eyesight, cone cells are responsible for color vision. From there, it is important to understand how color is perceived. Using the cone cells in the retina, we perceive images in color. Each type of cone specifically sees in regions of red, green, or blue, (RGB), in the color spectrum of red, orange, yellow, green, blue, indigo, violet.

The colors in between these absolutes are seen as different linear combinations of RGB. This is why TVs and computer screens are made up of thousands of little red, green, or blue lights, and why colors in electronic form are represented by different values of RGB. These values are usually given in the value of their frequency in log form.

YUV Color Space

The human eye is more sensitive to intensity changes than color changes, which is why it is acceptable to use black and white photography in place of color and why people can still distinguish everything in the photo without colors. The intensity, or luminance Y, can be found from the following equation:

$$\mathrm{Y}=0.3\mathrm{R}+0.6\mathrm{G}+0.1\mathrm{B}$$
$$\mathrm{Y}=0.3\mathrm{R}+0.6\mathrm{G}+0.1\mathrm{B} \tag{5.1.1}$$

The prior equation deals with the luminance, but the chrominance (dealing with colors) can be found from the following equations:

$$\mathrm{U}=0.5(\mathrm{BY})$$
$$\mathrm{U}=0.5(\mathrm{B}-\mathrm{Y}) \tag{5.1.2}$$
$$\mathrm{V}=0.625(\mathrm{R}-\mathrm{Y})$$
$$\mathrm{V}=0.625(\mathrm{RY}) \tag{5.1.3}$$

You can go from RGB to YUV color spaces with the following matrix operation:

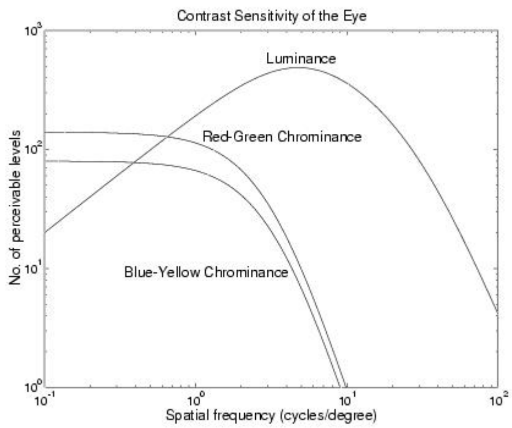
$$\begin{pmatrix} \mathrm{Y} \\ \mathrm{U} \\ \mathrm{V} \end{pmatrix} = \mathrm{C} * \begin{pmatrix} \mathrm{R} \\ \mathrm{G} \\ \mathrm{B} \end{pmatrix} \tag{5.1.4}$$

Where C is equal to:

$$\begin{pmatrix} 0.3 & 0.6 & 0.1 \\ -0.15 & -0.3 & 0.45 \\ 0.4375 & -0.3750 & -0.0625 \end{pmatrix} \tag{5.1.5}$$

Visual Sensitivity

In, we can see that



Visual Sensitivity: This graph shows the sensitivity of the eye to luminance (Y) and chrominance (U, V) components of images. The horizontal scale is spatial frequency, and represents the frequency of an alternating pattern of parallel stripes with sinusoidally varying intensity. The vertical scale is the contrast sensitivity of human vision, which is the ratio of the maximum visible range of intensities to the minimum discernible peak-to-peak intensity variation at the specified frequency.

- the maximum sensitivity to Y occurs for spatial frequencies around 5 cycles / degree, which corresponds to striped patterns with a half-period (stripe width) of 1.8 mm at a distance of 1 m (~arm's length).
- The eye has very little response above 100 cycles / degree, which corresponds to a stripe width of 0.1 mm at 1 m. On a standard PC display of width 250 mm, this would require 2500 pels per line! Hence the current SVGA standard of 1024×768 pels still falls somewhat short of the ideal and is limited by CRT spot size. Modern laptop displays have a pel size of about 0.3 mm, but are pleasing to view because the pel edges are so sharp (and there is no flicker).
- The sensitivity to luminance drops off at low spatial frequencies, showing that we are not very good at estimating absolute luminance levels as long as they do not change with time – the luminance sensitivity to temporal fluctuations (flicker) does not fall off at low spatial frequencies.
- The maximum chrominance sensitivity is much lower than the maximum luminance sensitivity with blue-yellow (U) sensitivity being about half of red-green (V) sensitivity and about 16 of the maximum luminance sensitivity.
- The chrominance sensitivities fall off above 1 cycle / degree, requiring a much lower spatial bandwidth than luminance.

We can now see why it is better to convert to the YUV domain before attempting image compression. The U and V components may be sampled at a lower rate than Y (due to narrower bandwidth) and may be quantified more coarsely (due to lower contrast sensitivity).

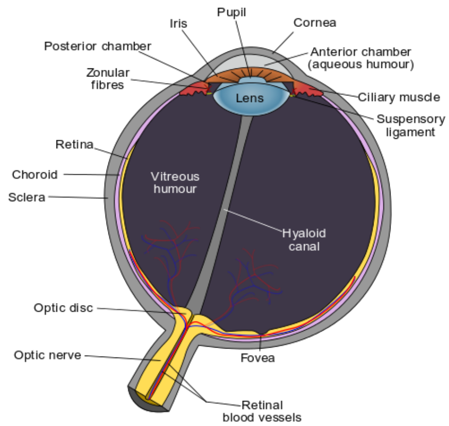
Resolution of the Human Eye

The human eye is a sense organ that allows vision and is capable to distinguish about 10 million colors.

learning objectives

- Describe field of view and color sensitivity of the human eye

The human eye is an organ that reacts to light in many circumstances. As a conscious sense organ the human eye allows vision; rod and cone cells in the retina allow conscious light perception and vision, including color differentiation and the perception of depth. The human eye can distinguish about 10 million colors. A model of the human eye can be seen in.



Schematic Diagram of the Human Eye: Structure of the eye and closeup of the retina.

The retina of human eye has a static contrast ratio of around 100:1 (about 6.5 f-stops). As soon as the eye moves, it re-adjusts its exposure, both chemically and geometrically, by adjusting the iris (which regulates the size of the pupil). Initial dark adaptation takes place in approximately four seconds of profound, uninterrupted darkness; full adaptation, through adjustments in retinal chemistry, is mostly complete in thirty minutes. Hence, a dynamic contrast ratio of about 1,000,000:1 (about 20 f-stops) is possible. The process is nonlinear and multifaceted, so an interruption by light starts the adaptation process over again. Full adaptation is dependent on good blood flow (thus dark adaptation may be hampered by poor circulation, and vasoconstrictors like tobacco).

The eye includes a lens not dissimilar to lenses found in optical instruments (such as cameras). The same principles can be applied. The pupil of the human eye is its aperture. The iris is the diaphragm that serves as the aperture stop. Refraction in the cornea causes the effective aperture (the entrance pupil) to differ slightly from the physical pupil diameter. The entrance pupil is typically about 4 mm in diameter, although it can range from 2 mm (f/8.3) in a brightly lit place to 8 mm (f/2.1) in the dark. The latter value decreases slowly with age; older people's eyes sometimes dilate to not more than 5-6mm.

The approximate field of view of an individual human eye is 95° away from the nose, 75° downward, 60° toward the nose, and 60° upward, allowing humans to have an almost 180-degree forward-facing horizontal field of view. With eyeball rotation of about 90° (head rotation excluded, peripheral vision included), horizontal field of view is as high as 170°. About 12–15° temporal and 1.5° below the horizontal is the optic nerve or blind spot which is roughly 7.5° high and 5.5° wide.

Nearsightedness, Farsidedness, and Vision Correction

In order for the human eye to see clearly, the image needs to be formed directly on the retina; if it is not, the image is blurry.

learning objectives

- Identify factors responsible for nearsightedness and farsightedness vision defects

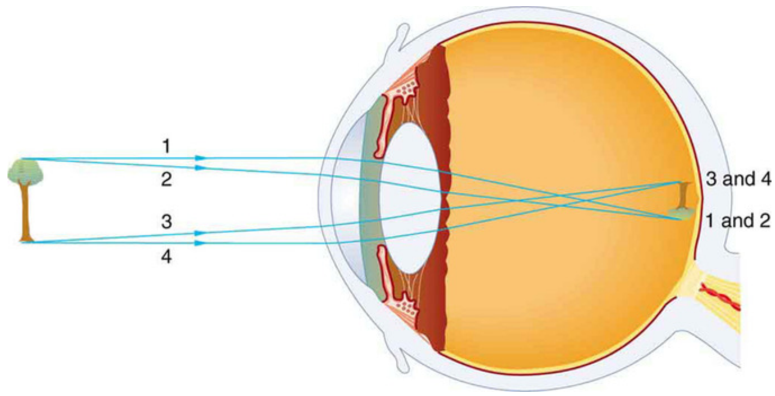
The human eye is the gateway to one of our five senses. The human eye is an organ that reacts with light. It allows light perception, color vision, and depth perception, but not all eyes are perfect. A normal human eye can see about 10 million different colors!

Properties

Contrary to what you might think, the human eye is not a perfect sphere, but is made up of two differently shaped pieces, the cornea and the sclera. These two parts are connected by a ring called the limbus. The part of the eye that is seen is the iris, which is the colorful part of the eye. In the middle of the iris is the pupil, which is the black dot that changes size. The cornea covers these elements, but it is transparent. The fundus is on the opposite of the pupil, but inside the eye and cannot be seen without special instruments. The optic nerve is what conveys the signals of the eye to the brain. shows a diagram of the eye.

Vision

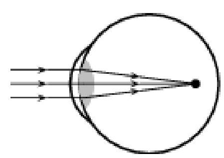
The different parts of the eye have different refractive indexes, and this is what bends the rays to form an image. The cornea provides two-thirds of the power to the eye. The lens provides the remaining power. The image passes through several layers of the eye, but this happens in a way very similar to that of a convex lens. When the image finally reaches the retena, it is inverted, but the brain will correct this. For the vision to be clear, the image has to be formed directly on the retina. The focus needs to be changed, much like a camera, depending on the distance and size of the object. The eye's lens is flexible, and changes shape. This changes the focal length. The eye's ciliary muscles control the shape of the lens. When you focus on something, you squeeze or relax these muscles.



Vision Diagram: An image is formed on the retina with light rays converging most at the cornea and upon entering and exiting the lens. Rays from the top and bottom of the object are traced and produce an inverted real image on the retina. The distance to the object is drawn smaller than scale.

Near Sighted Vision

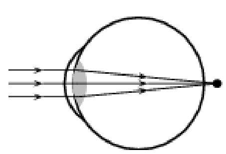
Nearsightedness, or myopia is a vision defect that occurs when the focus of the image is in front of the retina. This is shown in. Close objects are seen fine, but distant objects are blurry. This can be corrected by placing diverging lenses in front of the eye. This will cause the light rays to spread out before they enter the eye.



Near Sighted Vision: This occurs when the image is formed before the retina

Far Sighted Vision

Farsightedness, or hyperopia, is a vision defect that occurs when the focus of the image is behind the retina. This is shown in. Distant objects are seen fine, but closer objects are blurry. This can be corrected by placing converging lenses in front of the eye. This will cause the light rays to slightly converge together before they enter the eye.



Far Sighted Vision: This occurs when the image is formed behind the retina

Key Points

- The eye is made up of a number of parts, including the iris, pupil, cornea, and retina.
- The eye has six muscles which control the eye movement, all providing different tension and torque.
- The eye works a lot like a camera, the pupil provides the f-stop, the iris the aperture stop, the cornea resembles a lens. The way that the image is formed is much like the way a convex lens forms an image.
- The cones in the retina are responsible for seeing colors. There are three types of cones, each type can only pick up one color: red, green, or blue. This is why TVs and computer screens are made up of thousands of little red, green, or blue lights.
- The human eye is more sensitive to intensity changes than color changes, which is why it is acceptable to use black and white photography in place of color and why people can still distinguish everything in the photo without colors.
- Colors are usually written in different values of red, green, or blue. Each value is the log form of that frequency.
- The retina of human eye has a static contrast ratio of around 100:1 and a dynamic contrast ratio of about 1,000,000:1.
- The eye includes a lens not dissimilar to lenses found in optical instruments, such as cameras.
- The approximate field of view of an individual human eye is 95° away from the nose, 75° downward, 60° toward the nose, and 60° upward, allowing humans to have an almost 180-degree forward-facing horizontal field of view.
- The focal point of the image will change depending on how the lens is shaped. Your lens changes depending on the distance of the object, by the relaxation or contraction of the muscles, and this controls the focal length.
- Near sightedness occurs when the image is formed before the retina.
- Farsightedness occurs when the image is formed behind the retina.

Key Terms

- **pupil**: The hole in the middle of the iris of the eye, through which light passes to be focused on the retina.
- **aperture**: The diameter of the aperture that restricts the width of the light path through the whole system. For a telescope, this is the diameter of the objective lens (e.g., a telescope may have a 100 cm aperture).
- **luminance**: The intensity of an object, independent from its color.
- **static contrast ratio**: Luminosity ratio of the brightest and darkest color the system is capable of processing simultaneously at any instant of time.
- **dynamic contrast ratio**: Luminosity ratio of the brightest and darkest color the system is capable of processing over time (while the picture is moving).
- **field of view**: The angular extent of what can be seen, either with the eye or with an optical instrument or camera.
- **myopia**: A disorder of the vision where distant objects appear blurred because the eye focuses their images in front of the retina instead of on it.
- **hyperopia**: A disorder of the vision where the eye focusses images behind the retina instead of on it, so that distant objects can be seen better than near objects.

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5.2: Other Optical Instruments

A magnifying glass is a convex lens that lets the observer see a larger image of the object under observation. The lens is usually mounted in a frame with a handle, as shown below.

Magnifying Glass: A magnifying glass is a convex lens that lets the observer see a larger image of the object under observation.

The magnification of a magnifying glass depends upon where the instrument is placed between the user's eye and the object being viewed and upon the total distance between eye and object. The magnifying power is the ratio of the sizes of the images formed on the user's retina with and without the magnifying glass. When not using the lens, the user would typically bring the object as close to the eye as possible without it becoming blurry. (This point, known as the near point, varies with age. In a young child its distance can be as short as five centimeters, while in an elderly person its distance may be as long as one or two meters.) Magnifiers are typically characterized using a "standard" value of 0.25m.

The highest magnifying power is obtained by putting the lens very close to the eye and moving both the eye and the lens together to obtain the best focus. When the lens is used this way, the magnifying power can be found with the following equation:

$$\mathrm{MP}_0 = \frac{1}{4} \cdot \Phi + 1 \tag{5.2.1}$$

where Φ= optical power. When the magnifying glass is held close to the object and the eye is moved away, the magnifying power is approximated by:

$$\mathrm{MP}_0 = \frac{1}{4} \cdot \Phi \tag{5.2.2}$$

Typical magnifying glasses have a focal length of 25cm and an optical power of four diopters. This type of glass would be sold as a 2x magnifier, but a typical observer would see about one to two times magnification depending on the lens position.

The earliest evidence of a magnifying device was Aristophanes's "lens" from 424 BC, a glass globe filled with water. (Seneca wrote that it could be used to read letters "no matter how small or dim.") Roger Bacon described the properties of magnifying glasses in the 13th century, and eyeglasses were also developed in 13th-century Italy.

The Camera

Cameras are optical devices that allow a user to record an image of an object, either on photo paper or digitally.

What is a Camera?

A camera is a device that allows you to record images, either on film or digitally. Cameras can record images as well as movies; movies themselves got their name from moving pictures. The word camera comes from the Latin phrase *camera obscura*, which means "dark chamber. " The camera obscura was an early instrument for projecting images from slides. The camera that you use today is an evolution of the camera obscura.

A camera is usually comprised of an opening, or aperture, that allows light to enter into a hollow area and a surface that records the light at the other end. In the 20th century, these images would be stored on photographic paper that then had to be developed, but now most cameras store images digitally.

How does a Camera Work?

Cameras have a lot of components that allow them to work. Let's look at them one at a time.

The Lens

The camera lens allows the light to enter into the camera and is typically convex. There are many types of lenses that can be used, each for a different type of photography. There are lenses for close-ups, for sports, for architecture, and for portraits.

The two major features of a lens are focal length and aperture. The focal length determines the magnification of the image, and the aperture controls the light intensity. The f-number on a camera controls the shutter speed. This is the speed at which the shutter, which acts as its "eyelid," opens and closes. The larger the aperture, the smaller the f-number must be in order to get the shutter opened and closed fully. The time it takes to open and close the shutter is called the exposure. shows an example of two lenses of the same size but with different apertures.

Focus

Some cameras have a fixed focus, and only objects of a certain size at a certain distance from the camera will be in focus. Other cameras allow you to manually or automatically adjust the focus. shows a picture taken with a camera with manual focus; this allows the user to determine which objects will be in focus and which will not. The range of distance within which objects appear sharp and clear is called the depth of field.

Exposure

The aperture controls the intensity of the light entering the camera, and the shutter controls the exposure — the amount of time that the light is allowed into the camera.

Shutter

The shutter is what opens and closes to allow light through the aperture. The speed at which it opens and closes is called the f-number. For a larger aperture, the f-number is generally small for a quick shutter speed. For a smaller aperture, the f-number is larger, allowing for a slower shutter speed.

The Compound Microscope

A compound microscope is made of two convex lenses; the first, the ocular lens, is close to the eye, and the second is the objective lens.

A compound microscope uses multiple lenses to magnify an image for an observer. It is made of two convex lenses: the first, the ocular lens, is close to the eye; the second is the objective lens.

Compound microscopes are much larger, heavier and more expensive than simple microscopes because of the multiple lenses. The advantages of these microscopes, due to the multiple lenses, are the reduced chromatic aberrations and exchangeable objective lenses to adjust magnification.

shows a diagram of a compound microscope made from two convex lenses. The first lens is called the objective lens and is closest to the object being observed. The distance between the object and the objective lens is slightly longer than the focal length, f_0. The objective lens creates an enlarged image of the object, which then acts as the object for the second lens. The second or ocular lens is the eyepiece. The distance between the objective lens and the ocular lens is slightly shorter than the focal length of the ocular lens, f_e. This causes the ocular lens to act as a magnifying glass to the first image and makes it even larger. Because the final image is inverted, it is farther away from the observer's eye and thus much easier to view.

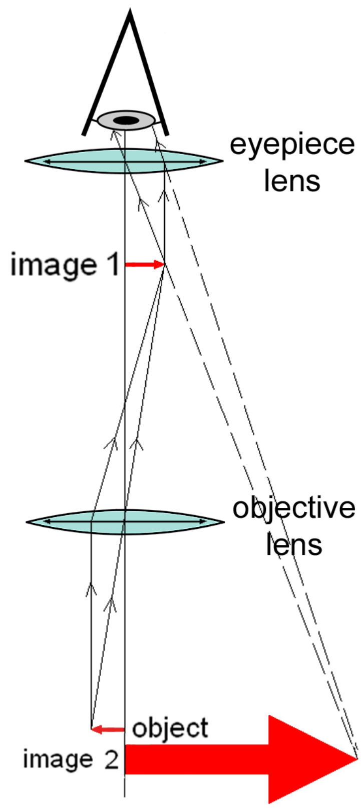


Diagram of a Compound Microscope: This diagram shows the setup of mirrors that allow for the magnification of images.

Since each lens produces a magnification that multiplies the height of the image, the total magnification is a product of the individual magnifications. The equation for calculating this is as follows:

$$\mathrm{m} = \mathrm{m_o m_e} \tag{5.2.3}$$

where m is total magnification, $\mathrm{m_o}$ is objective lens magnification, $\mathrm{m_e}$ is ocular lens magnification.

The Telescope

The telescope aids in observation of remote objects by collecting electromagnetic radiation, such as visible light.

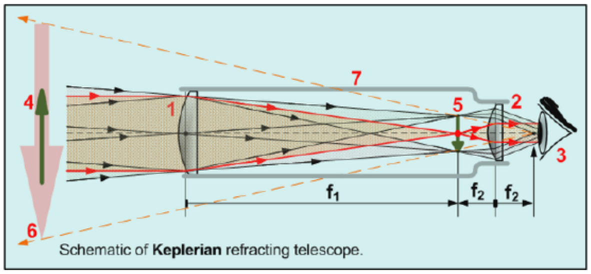
The telescope aids in observation of remote objects by collecting electromagnetic radiation, such as x-rays, visible light, infrared, and submillimeter rays. The first telescopes were invented in the Netherlands in the 1600s and used glass lenses. Shortly after, people began to build them using mirrors and called them reflecting telescopes.

History

The first telescope was a refracting telescope made by spectacle makers in the Netherlands in 1608. In 1610, Galileo made his own improved design. After the refracting telescope was invented, people began to explore the idea of a telescope that used mirrors. The potential advantages of using mirrors instead of lenses were a reduction in spherical aberrations and the elimination of chromatic aberrations. In 1668, Newton built the first practical reflecting telescope. With the invention of achromatic lenses in 1733, color aberrations were partially corrected, and shorter, more functional refracting telescopes could be constructed. Reflecting telescopes were not practical because of the highly corrosive metals used to make mirrors until the introduction of silver-coated glass mirrors in 1857.

Types of Telescopes

Refracting Telescopes



Schematic of **Keplerian** refracting telescope.

Schematic of Keplerian Refracting Telescope: All refracting telescopes use the same principles. The combination of an objective lens 1 and some type of eyepiece 2 is used to gather more light than the human eye is able to collect on its own, focus it 5, and present the viewer with a brighter, clearer, and magnified virtual image 6.

The figure above is a diagram of a refracting telescope. The objective lens (at point 1) and the eyepiece (point 2) gather more light than a human eye can collect by itself. The image is focused at point 5, and the observer is shown a brighter, magnified virtual image at point 6. The objective lens refracts, or bends, light. This causes the parallel rays to converge at a focal point, and those that are not parallel converge on a focal plane.

Reflecting Telescopes

Reflecting telescopes, such as the one shown in, use either one or a combination of curved mirrors that reflect light to form an image. They allow an observer to view objects that have very large diameters and are the primary type of telescope used in astronomy. The object being observed is reflected by a curved primary mirror onto the focal plane. (The distance from the mirror to the focal plane is called the focal length.) A sensor could be located here to record the image, or a secondary mirror could be added to redirect the light to an eyepiece.

Catadioptric Telescopes

Catadioptric telescopes, such as the one shown in, combine mirrors and lenses to form an image. This system has a greater degree of error correction than other types of telescopes. The combination of reflective and refractive elements allows for each element to correct the errors made by the other.

X-Ray Diffraction

The principle of diffraction is applied to record interference on a subatomic level in the study of x-ray crystallography.

X-ray diffraction was discovered by Max von Laue, who won the Nobel Prize in physics in 1914 for his mathematical evaluation of observed x-ray diffraction patterns.

Diffraction is the irregularities caused when waves encounter an object. You have most likely observed the effects of diffraction when looking at the bottom of a CD or DVD. The rainbow pattern that appears is a result of the light being interfered by the pits and lands on the disc that hold the data. shows this effect. Diffraction can happen to any type of wave, not just visible light waves.

Bragg Diffraction

In x-ray crystallography, the term for diffraction is Bragg diffraction, which is the scattering of waves from a crystalline structure. William Lawrence Bragg formulated the equation for Bragg's law, which relates wavelength to the angle of incidence and lattice spacing. Refer to for a diagram of the following equation: $n\lambda=2d\sin(\theta)n\lambda=2d\sin(\theta)$

- n – numeric constant known as the order of the diffracted beam
- λ – wavelength
- d – distance between lattice planes
- θ – angle of diffracted wave

The waves will experience either constructive interference or destructive interference. Similarly, the x-ray beam that is diffracted off a crystal will have some parts that have stronger energy, and others that lose energy. This depends on the wavelength and the lattice spacing.

The X-ray Diffractometer

The XRD machine uses copper metal as the element for the x-ray source. Diffraction patterns are recorded over an extended period of time, so it is very important that the beam intensity remains constant. Film used to be used to record the data, but that was inconvenient because it had to be replaced often. Now the XRD machines are equipped with semiconductor detectors. These XRD machines record images in two ways, either continuous scans or step scanning. In continuous scans, the detector moves in circular motions around the object, while a beam of x-ray is constantly shot at the detector. Pulses of energy are plotted with respect to diffraction angle. The step scan method is the more popular method. It is much more efficient than continuous scans. In this method, the detector collects data at a single fixed angle at a time. To ensure that the incident beam is continuous, XRD machines are equipped with a Soller slit. This acts like polarized sunglasses by organizing random x-ray beams into a stack of neatly arranged waves parallel to the plane of the detector.

X-Ray Imaging and CT Scans

Radiography uses x-rays to view material that cannot be seen by the human eye by identifying areas of different density and composition.

Overview

X-ray imaging, or radiography, used x-rays to view material within the body that cannot be seen by the human eye by identifying areas of different density and composition. CT Scans use the assistance of a computer to take this information, and generate 3 dimensional images.

X-ray Imaging

X-ray radiographs are produced by projecting a beam of X-rays toward an object, in medical cases, a part of the human body. Depending on the physical properties of the object (density and composition), some of the X-rays can be partially absorbed. The portion of the rays that are not absorbed then pass through the object and are recorded by either film or a detector, like in a camera. This provides the observer with a 2 dimensional representation of all the components of that object superimposed on each other. shows an image of a human elbow.

X-Ray Radiography: Radiography of the knee in a modern X-ray machine.

Tomography

Tomography refers to imaging by sections, or sectioning. demonstrates this concept. The three-dimensional image is broken down into sections. (S_1) shows a section from the left and (S_2) shows a section from the right.

CT Scans

CT scans, or computed tomography scans use a combination of X-ray radiography and tomography to produce slices of areas of the human body. Doctors can analyze the area, and based on the ability of the material to block the X-ray beam, understand more about the material. shows a CT Scan of a human brain. Doctors can cross reference the images with known properties of the same material and determine if there are any inconsistencies or problems. Although generally these scans are shown as in, the information recorded can be used to create a 3 dimensional image of the area. shows a three dimensional image of a brain that was made by compiling CT Scans.

Specialty Microscopes and Contrast

Microscopes are instruments that let the human eye see objects that would otherwise be too small.

Microscopes are instruments that let the human eye see objects that would otherwise be too small. There are many types of microscopes: optical microscopes, transmission electron microscopes, scanning electron microscopes and scanning probe microscopes.

Microscope Classes

One way to group microscopes is based on how the image is generated through the microscope. Here are three ways we can classify microscopes:

1.) Light or Photon – optical microscopes

2.) Electrons – electron microscopes

3.) Probe – scanning probe microscopes.

Microscopes can also be classified based on whether they analyze the sample by scanning a point at a time (scanning electron microscopes), or by analyzing the entire sample at once (transmission electron microscopes).

Types of Microscopes

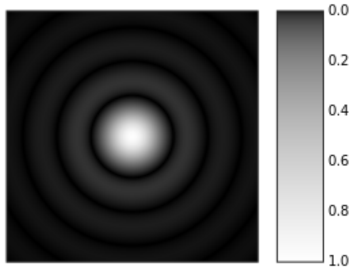
- In optical microscopes, the better the contrast between the image and the surface it is being viewed on, the better the resolution will be to the viewer. There are many illumination techniques to generate improved contrast. These techniques include “dark field” and “bright field.” With the dark field technique the light is scattered by the object and the image appears to the observer on a dark background. With the bright field technique the object is illuminated from below to increase the contrast in the image seen by viewers.
- Transmission Electron Microscope: The TEM passes electrons through the sample, and allows people to see objects that are normally not seen by the naked eye. A beam of electrons is transmitted through an ultra thin specimen, interacting with the specimen as it passes through. This interaction forms an image that is magnified and focused onto an imaging device.
- Scanning Electron Microscopes: Referred to as SEM, these microscopes look at the surface of objects by scanning them with a fine electron beam. The electron beam of the microscope interacts with the electrons in the sample and produces signals that can be detected and have information about the topography and composition.
- Atomic Force Microscopy: The AFM is a scanning probe type of microscopy with very high resolution and is one of the foremost tools for imaging at the nanoscale. The mechanical probe feels the surface with a cantilever with a sharp tip. The deflection of the tip is then measured using a laser spot that is reflected from the surface of the cantilever.

Limits of Resolution and Circular Aperatures

In optical imaging, there is a fundamental limit to the resolution of any optical system that is due to diffraction.

The resolution of an optical imaging system (e.g., a microscope, telescope, or camera) can be limited by factors such as imperfections in the lenses or misalignment. However, there is a fundamental maximum to the resolution of any optical system that is due to diffraction (a wave nature of light). An optical system with the ability to produce images with angular resolution as good as the instrument’s theoretical limit is said to be diffraction limited.

For telescopes with circular apertures, the size of the smallest feature in an image that is diffraction limited is the size of the Airy disc, as shown in. As one decreases the size of the aperture in a lens, diffraction increases and the ring features from diffraction become more prominent. Similarly, when imaged objects get smaller, features from diffraction begin to blur the boundary of the object. Since effects of diffraction become most prominent for waves whose wavelength is roughly similar to the dimensions of the diffracting objects, the wavelength of the imaging beam sets a fundamental limit on the resolution of any optical system.



Airy Disk: Computer-generated image of an Airy disk. The gray scale intensities have been adjusted to enhance the brightness of the outer rings of the Airy pattern.

The Abbe Diffraction Limit for a Microscope

The observation of sub-wavelength structures with microscopes is difficult because of the Abbe diffraction limit. In 1873, Ernst Abbe found that light, with wavelength λ, traveling in a medium with refractive index n, cannot be converged to a spot with a radius less than:

$$\mathrm{d}=\frac{\lambda}{2(\mathrm{n}\sin\theta)} \tag{5.2.4}$$

The denominator nsinθnsinθ is called the numerical aperture and can reach about 1.4 in modern optics, hence the Abbe limit is roughly d=λ/2. With green light around 500 nm, the Abbe limit is 250 nm which is large compared to most nanostructures, or biological cells with sizes on the order of 1μm and internal organelles which are much smaller. Using a 500 nm beam, you cannot (in principle) resolve any features with size less than around 250 nm.

Improving Resolution

To increase the resolution, shorter wavelengths can be used such as UV and X-ray microscopes. These techniques offer better resolution but are expensive, suffer from lack of contrast in biological samples and may damage the sample. There are techniques for producing images that appear to have higher resolution than allowed by simple use of diffraction-limited optics. Although these techniques improve some aspect of resolution, they generally involve an enormous increase in cost and complexity. Usually the technique is only appropriate for a small subset of imaging problems.

Aberrations

An aberration, or distortion, is a failure of rays to converge at one focus because of limitations or defects in a lens or mirror.

The Basics of Aberrations

An aberration is the failure of rays to converge at one focus because of limitations or defects in a lens or mirror. Basically, an aberration is a distortion of an image due to the fact that lenses will never behave exactly according to the way they were modeled. Types of aberrations vary due to the size, material composition, or thickness of a lens, or the position of an object.

Chromatic Aberration

A chromatic aberration, also called achromatism or chromatic distortion, is a distortion of colors. This aberration happens when the lens fails to focus all the colors on the same convergence point. This happens because lenses have a different index of refraction for different wavelengths of light. The refractive index decreases with increasing wavelength. These aberrations or distortions occur on the edges of color boundaries between bright and dark areas of an image. Since the index of refraction of lenses depends on color or wavelength, images are produced at different places and with different magnifications for different colors. shows chromatic aberration for a single convex lens. Since violet rays have a higher refractive index than red, they are bent more and focused closed to the lens. shows a two-lens system using a diverging lens to partially correct for this, but it is nearly impossible to do so completely.

The law of reflection is independent of wavelength, and therefore mirrors do not have this problem. This is why it is advantageous to use mirrors in telescopes and other optical systems.

Comatic Aberration

A comatic aberration, or coma, occurs when the object is off-center. Different parts of a lens of a mirror do not refract or reflect the image to the same point, as shown in. They can also be result of an imperfection in the lens or other component and result in off-axis point sources. These aberrations can cause objects to appear pear-shaped. They can also cause stars to appear distorted or appear to have tails, as with comets.

Other Aberrations

Spherical aberrations are a form of aberration where rays converging from the outer edges of a lens converge to a focus closer to the lens, and rays closer to the axis focus further. Astigmatisms are also a form of aberration in the lenses of the eyes where rays that propagate in two perpendicular planes have different foci. This can eventually cause a monochromatic image to distort vertically or horizontally. Another aberration or distortion is a barrel distortion where image magnification decreases with the distance from the optical axis. The apparent effect is that of an image which has been mapped around a sphere, like in a fisheye lens.

Key Points

- The magnification of a magnifying glass depends upon where it is placed between the user's eye and the object being viewed and upon the total distance between eye and object.
- The magnifying power is the ratio of the sizes of the images formed on the user's retina with and without the lens.
- The highest magnifying power is obtained by putting the lens very close to the eye and moving both the eye and the lens together to obtain the best focus.
- Cameras work very similarly to how the human eye works. The iris is similar to the lens; the pupil is similar to the aperture; and the eyelid is similar to the shutter.
- Cameras are a modern evolution of the camera obscura. The camera obscura was a device used to project images.
- The most important part of a camera is the lens, which allows the image to be magnified and focused. This can be done manually on some cameras and automatically on newer cameras.
- Movie cameras work by taking many pictures each second and then showing each image in order very quickly to give the effect that the pictures are moving. This is where the name "movie" comes from.
- A compound microscope uses multiple lenses to create an enlarged image that is easier for a human eye to see; this is due to the fact that the final image is farther away from the observer, and therefore the eye is more relaxed when viewing the image.
- The object is placed just beyond to focal length of the objective lens. An enlarged image is then captured by the objective lens, which acts as the object for the ocular lens. The ocular lens is closer to the new image than its focal length, causing it to act as a magnifying glass.
- Since the final image is just a multiple of the size of the first image, the final magnification is a product of both magnifications from each lens.
- Until the invention of silver-backed mirrors, refractive mirrors were the standard for use in telescopes. This was because of the highly corrosive nature of the metals used in older mirrors. Since then, reflective mirrors have replaced refractive mirrors in astronomy.
- There are three main types of optical telescopes: refractive, reflective, and catadioptric.
- Refractive telescopes, such as the one invented by Galileo, use an objective lens and an eyepiece. The image is focused at the focal point and allows the observer to see a brighter, larger image than they would with their own eye.
- Reflective telescopes use curved mirrors that reflect light to form an image. Sometimes a secondary mirror redirects the image to an eyepiece. Other times the image is recorded by a sensor and observed on a computer screen.
- Catadioptric telescopes combine mirrors and lenses to form an image. This system has a greater degree of error correction than other types of telescopes. The combination of reflective and refractive elements allows for each element to correct the errors made by the other.
- Diffraction is what happens when waves encounter irregularities on a surface or object and are caused to interfere with each other, either constructively or destructively.
- The Bragg law pertains to applying the laws of diffraction to crystallography in order to obtain precise images of the lattice structures in atoms.
- The x-ray diffractometer is the machine used to scan the object by shooting a wave at it and recording the interference it encounters.

- Most XRDs are equipped with a Soller slit, which acts like a polarizer for the incident beam. It makes sure that the incident beam being recorded is perfectly parallel to the object being analyzed.
- Radiography uses x-rays to take pictures of materials with in an object that can not be seen. They shoot x-ray beams through the object, and collect the rays on film or a detector on the other side. Some of the rays are absorbed into the denser materials, and this is how the image is produced.
- X-ray radiographs take images of all the materials within an object superimposed on each other.
- The traditional, superimposed images can be helpful for a number of applications, but CT scans enable the observer to see just the desired sections of a material.
- Modern CT scans can even take all the slices, or layers, and arrange them into a three-dimensional representation of the object.
- For better resolution, it is important that there is a lot of contrast between the image and the background.
- Microscopes are classified by what interacts with the object, such as light or electrons. They are also classified by whether they take images by scanning a little at a time or by taking images of the entire object at once.
- Some common types of specialty microscopes are scanning electron micrscopes (SEM), transmission electron microscopes (TEM), both of which are electron microscopes, and atomic force microscopes (ATM) which is a scanning probe microscope.
- Since effects of diffraction become most prominent for waves whose wavelength is roughly similar to the dimensions of the diffracting objects, the wavelength of the imaging beam sets a fundamental limit on the resolution of any optical system.
- The Abbe diffraction limit for a microscope is given as $\mathrm{d}=\frac{\lambda}{2(\mathrm{n}\sin\theta)}$.
- Since the diffraction limit is proportional to wavelength, to increase the resolution, shorter wavelengths can be used such as UV and X-ray microscopes.
- There are many types of aberrations, including chromatic, spherical, comatic, astigmatism, and barrel distortion.
- Chromatic aberrations occur due to the fact that lenses have different refractive indexes for different wavelengths, and therefore colors. These aberrations occur right on the edges of images between light and dark areas of the picture.
- Mirrors do not have chromatic aberrations because they do not rely on the index of refraction, but rather the index of reflection, which is independent of wavelength.
- Comatic aberrations are due to imperfections in lenses and cause the point source to be off-center. This can cause images to appear pear-shaped, or cause images to have tails, as with comets.

Key Terms

- **lens**: an object, usually made of glass, that focuses or defocuses the light that passes through it
- **diopter**: a unit of measure of the power of a lens or mirror, equal to the reciprocal of its focal length in meters. Myopia is diagnosed and measured in diopters
- **convex**: curved or bowed outward like the outside of a bowl or sphere or circle
- **shutter speed**: The duration of time for which the shutter of a camera remains open when exposing photographic film or other photosensitive material to light for the purpose of recording an image
- **chromatic aberration**: an optical aberration, in which an image has colored fringes, caused by differential refraction of light of different wavelengths
- **spherical aberration**: a type of lens aberration that causes blurriness, particularly away from the center of the lens
- **achromatic**: free from color; transmitting light without color-related distortion
- **constructive interference**: Occurs when waves interfere with each other crest to crest and the waves are exactly in phase with each other.
- **crystallography**: The experimental science of determining the arrangement of atoms in solids.
- **destructive interference**: Occurs when waves interfere with each other crest to trough (peak to valley) and are exactly out of phase with each other.
- **radiography**: The use of X-rays to view a non-uniformly composed material such as the human body.
- **tomography**: Imaging by sections or sectioning.
- **superimposed**: Positioned on or above something else, especially in layers
- **contrast**: A difference in lightness, brightness and/or hue between two colors that makes them more or less distinguishable
- **diffraction**: The bending of a wave around the edges of an opening or an obstacle.
- **nanostructure**: Any manufactured structure having a scale between molecular and microscopic.
- **aperture**: The diameter of the aperture that restricts the width of the light path through the whole system. For a telescope, this is the diameter of the objective lens (e.g., a telescope may have a 100 cm aperture).
- **distortion**: (optics) an aberration that causes magnification to change over the field of view.

- **refraction**: Changing of a light ray's direction when it passes through variations in matter.
- **aberration**: The convergence to different foci, by a lens or mirror, of rays of light emanating from one and the same point, or the deviation of such rays from a single focus; a defect in a focusing mechanism that prevents the intended focal point.

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CHAPTER OVERVIEW

6: Wave Optics

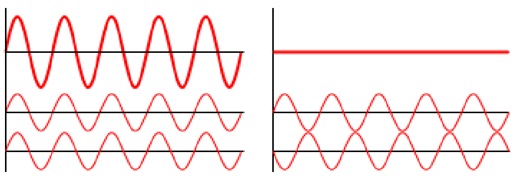
6.1: Superposition and Interference

learning objectives

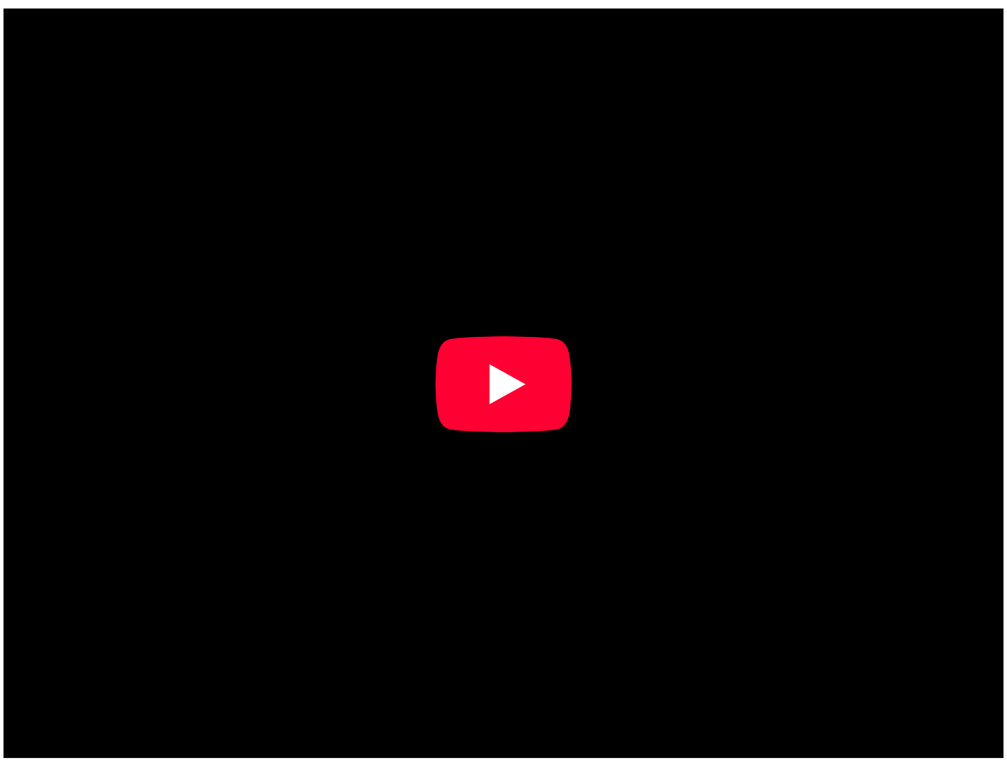
- Contrast the effects of constructive and destructive interference

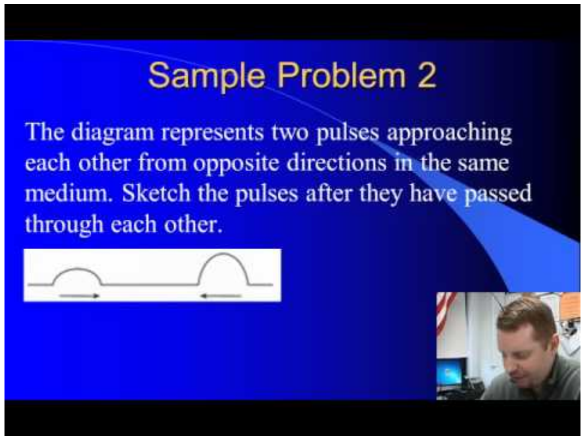
Conditions for Wave Interference

Interference is a phenomenon in which two waves superimpose to form a resultant wave of greater or lesser amplitude. Its effects can be observed in all types of waves (for example, light, acoustic waves and water waves). Interference usually refers to the interaction of waves that are correlated (coherent) with each other because they originate from the same source, or they have the same or nearly the same frequency. When two or more waves are incident on the same point, the total displacement at that point is equal to the vector sum of the displacements of the individual waves. If a crest of one wave meets a crest of another wave of the same frequency at the same point, then the magnitude of the displacement is the sum of the individual magnitudes. This is *constructive interference* and occurs when the phase difference between the waves is a multiple of 2π. *Destructive interference* occurs when the crest of one wave meets a trough of another wave. In this case, the magnitude of the displacements is equal to the difference in the individual magnitudes, and occurs when this difference is an odd multiple of π. Examples of constructive and destructive interference are shown in. If the difference between the phases is intermediate between these two extremes, then the magnitude of the displacement of the summed waves lies between the minimum and maximum values.



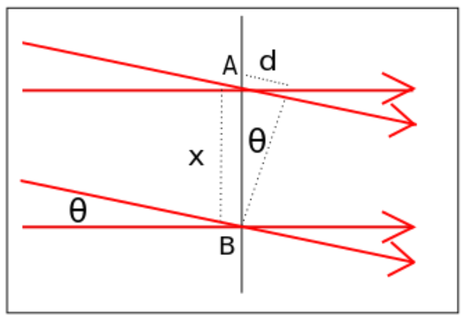
Wave Interference: Examples of constructive (left) and destructive (right) wave interference.





Wave Interference: A brief introduction to constructive and destructive wave interference and the principle of superposition.

A simple form of wave interference is observed when two waves of the same frequency (also called a plane wave) intersect at an angle, as shown in. Assuming the two waves are in phase at point B, then the relative phase changes along the *x*-axis. The phase difference at point A is given by:



Interference of Plane Waves: Geometrical arrangement for two plane wave interference.

$$\Delta\varphi = \frac{2\pi \mathrm{d}}{\lambda} = \frac{2\pi \mathrm{x}\sin\theta}{\lambda} \tag{6.1.1}$$

Constructive interference occurs when the waves are in phase, or

$$\frac{x\sin\theta}{\lambda} = 0, \pm 1, \pm 2, \ldots \tag{6.1.2}$$

Destructive interference occurs when the waves are half a cycle out of phase, or

$$\frac{x\sin\theta}{\lambda} = \pm\frac{1}{2}, \pm\frac{3}{2}, \ldots \tag{6.1.3}$$

Reflection Due to Phase Change

Light exhibits wave characteristics in various media as well as in a vacuum. When light goes from a vacuum to some medium (like water) its speed and wavelength change, but its frequency *f* remains the same. The speed of light in a medium is $v = c/n$, where *n* is the index of refraction. For example, water has an index of refraction of $n = 1.333$. When light is reflected off a medium with a higher index of refraction, crests get reflected as troughs and troughs get reflected as crests. In other words, the wave undergoes a 180 degree change of phase upon reflection, and the reflected ray “jumps” ahead by half a wavelength.

Air Wedge

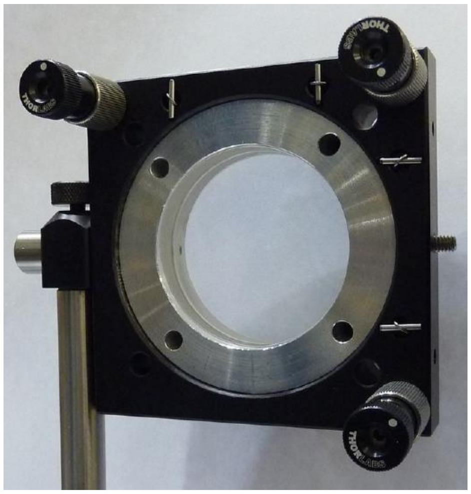
An air wedge is a simple interferometer used to visualize the disturbance of the wave front after propagation through a test object.

learning objectives

- Describe how an air wedge is used to visualize the disturbance of a wave front after proagation

Air Wedge

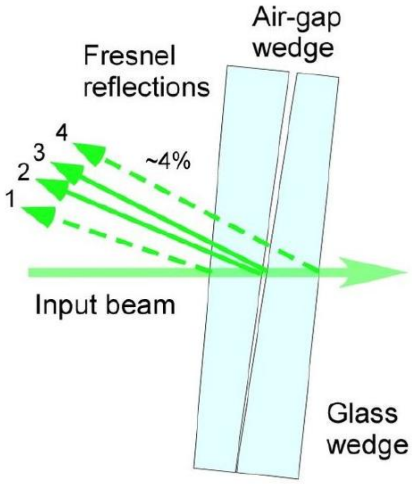
An air wedge is one of the simplest designs of shearing interferometers used to visualize the disturbance of the wave front after propagation through a test object. An air wedge can be used with nearly any light source, including non-coherent white light. The interferometer consists of two optical glass wedges (~2-5 degrees), pushed together and then slightly separated from one side to create a thin air-gap wedge. An example of an air wedge interferometer is shown in.



Air Wedge: Example of air wedge interferometer

The air gap between the two glass plates has two unique properties: it is very thin (micrometer scale) and has perfect flatness. Because of this extremely thin air-gap, the air wedge interferometer has been successfully used in experiments with femto-second high-power lasers.

An incident beam of light encounters four boundaries at which the index of refraction of the media changes, causing four reflected beams (or Fresnel reflections) as shown in. The first reflection occurs when the beam enters the first glass plate. The second reflection occurs when the beam exits the first plate and enters the air wedge, and the third reflection occurs when the beam exits the air wedge and enters the second glass plate. The fourth beam is reflected when it encounters the boundary of the second glass plate. The air wedge angle, between the second and third Fresnel reflections, can be adjusted, causing the reflected light beams to constructively and destructively interfere and create a fringe pattern. To minimize image aberrations of the resulting fringes, the angle plane of the glass wedges has to be placed orthogonal to the angle plane of the air-wedge.



Light Reflections Inside an Air Wedge Interferometer: Beam path inside of air wedge interferometer

Newton’s Rings

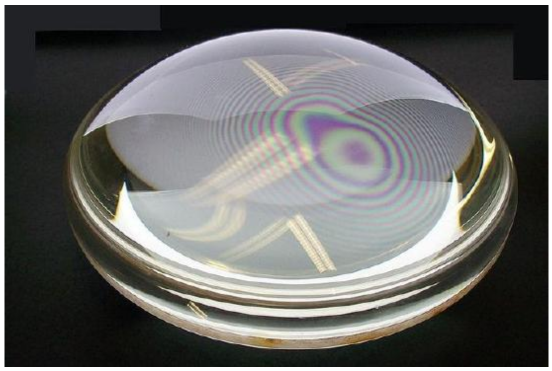
Newton’s rings are a series of concentric circles centered at the point of contact between a spherical and a flat surface.

learning objectives

- Apply Newton’s rings to determine light characteristics of a lens

Newton’s Rings

In 1717, Isaac Newton first analyzed an interference pattern caused by the reflection of light between a spherical surface and an adjacent flat surface. Although first observed by Robert Hooke in 1664, this pattern is called Newton’s rings, as Newton was the first to analyze and explain the phenomena. Newton’s rings appear as a series of concentric circles centered at the point of contact between the spherical and flat surfaces. When viewed with monochromatic light, Newton’s rings appear as alternating bright and dark rings; when viewed with white light, a concentric ring pattern of rainbow colors is observed. An example of Newton’s rings when viewed with white light is shown in the figure below.



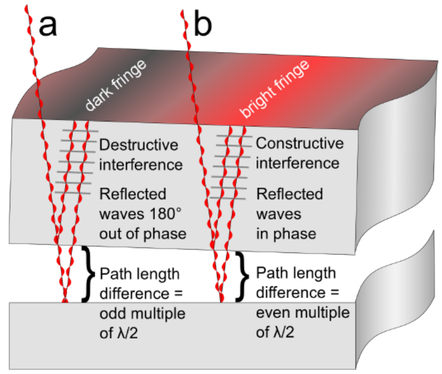
Newton’s Rings in a drop of water: Newton’s rings seen in two plano-convex lenses with their flat surfaces in contact. One surface is slightly convex, creating the rings. In white light, the rings are rainbow-colored, because the different wavelengths of each color interfere at different locations.

The light rings are caused by constructive interference between the light rays reflected from both surfaces, while the dark rings are caused by destructive interference. The outer rings are spaced more closely than the inner ones because the slope of the curved lens surface increases outwards. The radius of the Nth bright ring is given by:

$$\mathrm{r_N} = \left[\left(\mathrm{N} - \frac{1}{2}\lambda\mathrm{R}\right)\right]^{1/2} \tag{6.1.4}$$

where N is the bright-ring number, R is the radius of curvature of the lens the light is passing through, and λ is the wavelength of the light passing through the glass.

A spherical lens is placed on top of a flat glass surface. An incident ray of light passes through the curved lens until it comes to the glass-air boundary, at which point it passes from a region of higher refractive index *n* (the glass) to a region of lower *n* (air). At this boundary, some light is transmitted into the air, while some light is reflected. The light that is transmitted into the air does not experience a change in phase and travels a a distance, *d*, before it is reflected at the flat glass surface below. This second air-glass boundary imparts a half-cycle phase shift to the reflected light ray because air has a lower *n* than the glass. The two reflected light rays now travel in the same direction to be detected. As one gets farther from the point at which the two surfaces touch, the distance *d*increases because the lens is curving away from the flat surface.



Formation of Interference Fringes: This figure shows how interference fringes form.

If the path length difference between the two reflected light beams is an odd multiple of the wavelength divided by two, $\lambda/2$, the reflected waves will be 180 degrees out of phase and destructively interfere, causing a dark fringe. If the path-length difference is an even multiple of $\lambda/2$, the reflected waves will be in phase with one another. The constructive interference of the two reflected waves creates a bright fringe.

Key Points

- When two or more waves are incident on the same point, the total displacement at that point is equal to the vector sum of the displacements of the individual waves.
- Light exhibits wave characteristics in various media as well as in a vacuum. When light goes from a vacuum to some medium, like water, its speed and wavelength change, but its frequency f remains the same.
- When light is reflected off a medium with a higher index of refraction, crests get reflected as troughs and troughs get reflected as crests. In other words, the wave undergoes a 180 degree change of phase upon reflection, and the reflected ray “jumps” ahead by half a wavelength.
- An air wedge interferometer consists of two optical glass wedges (~2-5 degrees), pushed together and then slightly separated from one side to create a thin air-gap wedge.
- The air gap between the two glass plates has two unique properties: it is very thin (micrometer scale) and has perfect flatness.
- To minimize image aberrations of the resulting fringes, the angle plane of the glass wedges has to be placed orthogonal to the angle plane of the air wedge.
- When viewed with monochromatic light, Newton’s rings appear as alternating bright and dark rings; when viewed with white light, a concentric ring pattern of rainbow colors is observed.
- If the path length difference between the two reflected light beams is an odd multiple of the wavelength divided by two, $\lambda/2$, the reflected waves will be 180 degrees out of phase and destructively interfere, causing a dark fringe.
- If the path length difference is an even multiple of $\lambda/2$, the reflected waves will be in-phase with one another. The constructive interference of the two reflected waves creates a bright fringe.

Key Terms

- **coherent**: Of waves having the same direction, wavelength and phase, as light in a laser.
- **plane wave**: A constant-frequency wave whose wavefronts (surfaces of constant phase) are infinite parallel planes of constant peak-to-peak amplitude normal to the phase velocity vector.
- **orthogonal**: Of two objects, at right angles; perpendicular to each other.
- **interferometer**: Any of several instruments that use the interference of waves to determine wavelengths and wave velocities, determine refractive indices, and measure small distances, temperature changes, stresses, and many other useful measurements.
- **wavelength**: The length of a single cycle of a wave, as measured by the distance between one peak or trough of a wave and the next; it is often designated in physics as λ, and corresponds to the velocity of the wave divided by its frequency.
- **lens**: an object, usually made of glass, that focuses or defocuses the light that passes through it
- **monochromatic**: Describes a beam of light with a single wavelength (i.e., of one specific color or frequency).

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6.2: Diffraction

learning objectives

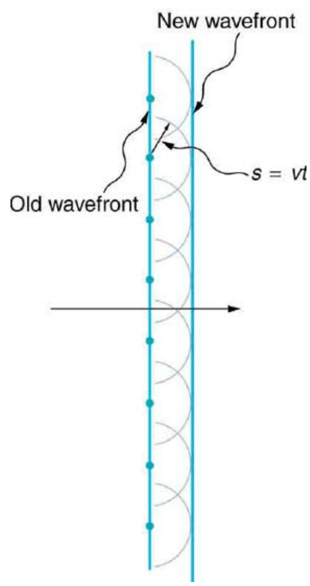
- Formulate Huygens's Principle

Overview

The Huygens-Fresnel principle states that every point on a wavefront is a source of wavelets. These wavelets spread out in the forward direction, at the same speed as the source wave. The new wavefront is a line tangent to all of the wavelets.

Background

Christiaan Huygens was a Dutch scientist who developed a useful technique for determining how and where waves propagate. In 1678, he proposed that every point that a luminous disturbance touches becomes itself a source of a spherical wave. The sum of the secondary waves (waves that are a result of the disturbance) determines the form of the new wave. shows secondary waves traveling forward from their point of origin. He was able to come up with an explanation of the linear and spherical wave propagation, and derive the laws of reflection and refraction (covered in previous atoms) using this principle. He could not, however, explain what is commonly known as diffraction effects. Diffraction effects are the deviations from rectilinear propagation that occurs when light encounters edges, screens and apertures. These effects were explained in 1816 by French physicist Augustin-Jean Fresnel.



Straight Wavefront: Huygens's principle applied to a straight wavefront. Each point on the wavefront emits a semicircular wavelet that moves a distance s=vt. The new wavefront is a line tangent to the wavelets.

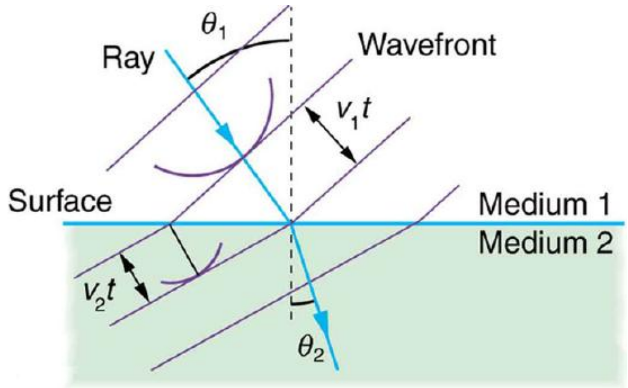
Huygens's Principle

Figure 1 shows a simple example of the Huygens's Principle of diffraction. The principle can be shown with the equation below:

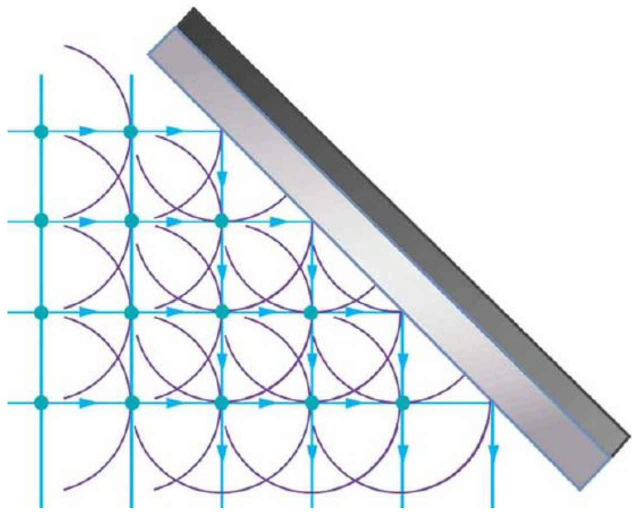
$$s = vt \tag{6.2.1}$$

where s is the distance, v is the propagation speed, and t is time.

Each point on the wavefront emits a wave at speed, v. The emitted waves are semicircular, and occur at t, time later. The new wavefront is tangent to the wavelets. This principle works for all wave types, not just light waves. The principle is helpful in describing reflection, refraction and interference. shows visually how Huygens's Principle can be used to explain reflection, and shows how it can be applied to refraction.



Huygens's Refraction: Huygens's principle applied to a straight wavefront traveling from one medium to another where its speed is less. The ray bends toward the perpendicular, since the wavelets have a lower speed in the second medium.



Reflection: Huygens's principle applied to a straight wavefront striking a mirror. The wavelets shown were emitted as each point on the wavefront struck the mirror. The tangent to these wavelets shows that the new wavefront has been reflected at an angle equal to the incident angle. The direction of propagation is perpendicular to the wavefront, as shown by the downward-pointing arrows.

Example 6.2.1:

This principle is actually something you have seen or experienced often, but just don't realize. Although this principle applies to all types of waves, it is easier to explain using sound waves, since sound waves have longer wavelengths. If someone is playing music in their room, with the door closed, you might not be able to hear it while walking past the room. However, if that person where to open their door while playing music, you could hear it not only when directly in front of the door opening, but also on a considerable distance down the hall to either side. is a direct effect of diffraction. When light passes through much smaller openings, called slits, Huygens's principle shows that light bends similar to the way sound does, just on a much smaller scale. We will examine in later atoms single slit diffraction and double slit diffraction, but for now it is just important that we understand the basic concept of diffraction.

Diffraction

As we explained in the previous paragraph, diffraction is defined as the bending of a wave around the edges of an opening or an obstacle.

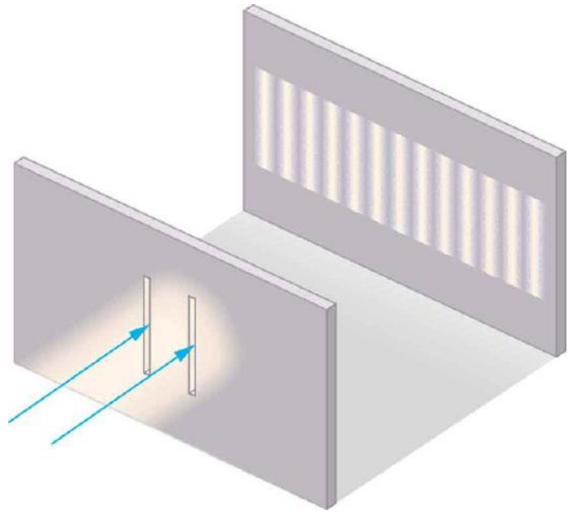
Young's Double Slit Experiment

The double-slit experiment, also called Young's experiment, shows that matter and energy can display both wave and particle characteristics.

learning objectives

- Explain why Young's experiment more credible than Huygens'

The double-slit experiment, also called Young's experiment, shows that matter and energy can display both wave and particle characteristics. As we discussed in the atom about the Huygens principle, Christiaan Huygens proved in 1628 that light was a wave. But some people disagreed with him, most notably Isaac Newton. Newton felt that color, interference, and diffraction effects needed a better explanation. People did not accept the theory that light was a wave until 1801, when English physicist Thomas Young performed his double-slit experiment. In his experiment, he sent light through two closely spaced vertical slits and observed the resulting pattern on the wall behind them. The pattern that resulted can be seen in.



Young's Double Slit Experiment: Light is sent through two vertical slits and is diffracted into a pattern of vertical lines spread out horizontally. Without diffraction and interference, the light would simply make two lines on the screen.

Wave-Particle Duality

The wave characteristics of light cause the light to pass through the slits and interfere with itself, producing the light and dark areas on the wall behind the slits. The light that appears on the wall behind the slits is scattered and absorbed by the wall, which is a characteristic of a particle.

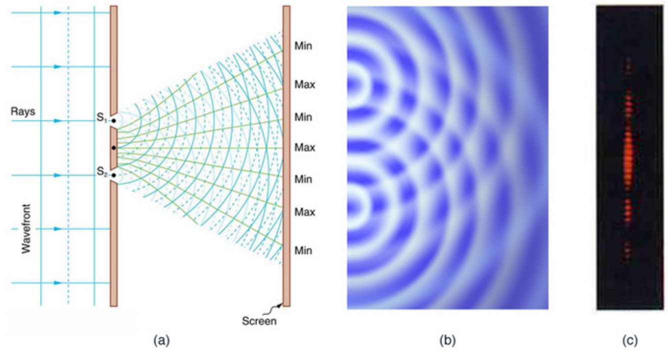
Young's Experiment

Why was Young's experiment so much more credible than Huygens'? Because, while Huygens' was correct, he could not demonstrate that light acted as a wave, while the double-slit experiment shows this very clearly. Since light has relatively short wavelengths, to show wave effects it must interact with something small — Young's small, closely spaced slits worked.

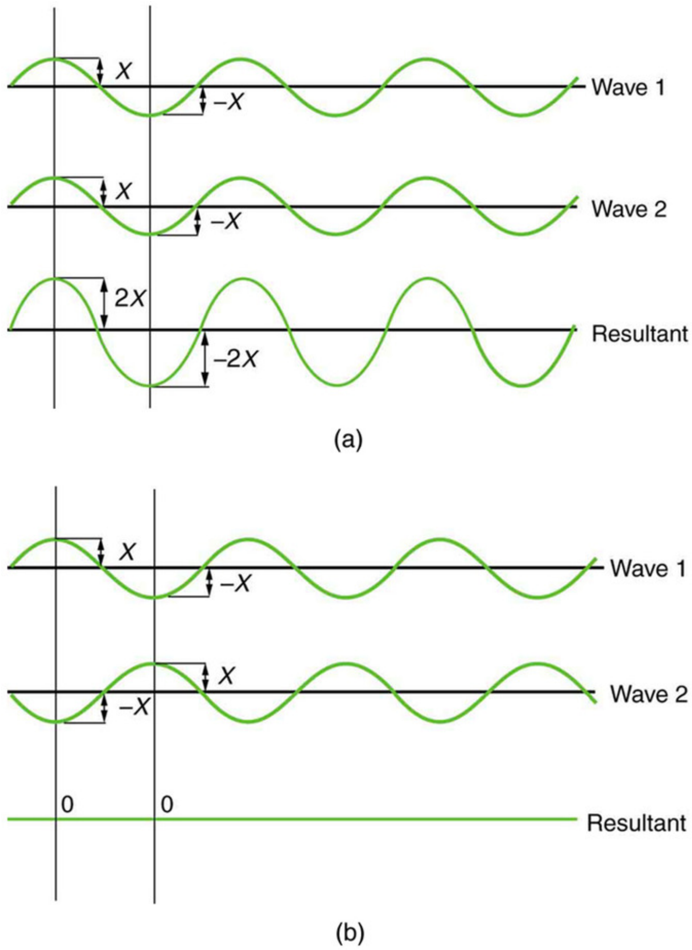
The example in uses two coherent light sources of a single monochromatic wavelength for simplicity. (This means that the light sources were in the same phase.) The two slits cause the two coherent light sources to interfere with each other either constructively or destructively.

Constructive and Destructive Wave Interference

Constructive wave interference occurs when waves interfere with each other crest-to-crest (peak-to-peak) or trough-to-trough (valley-to-valley) and the waves are exactly in phase with each other. This *amplifies* the resultant wave. Destructive wave interference occurs when waves interfere with each other crest-to-trough (peak-to-valley) and are exactly out of phase with each other. This cancels out any wave and results in no light. These concepts are shown in. It should be noted that this example uses a single, monochromatic wavelength, which is not common in real life; a more practical example is shown in.



Practical Constructive and Destructive Wave Interference: Double slits produce two coherent sources of waves that interfere. (a) Light spreads out (diffracts) from each slit because the slits are narrow. These waves overlap and interfere constructively (bright lines) and destructively (dark regions). We can only see this if the light falls onto a screen and is scattered into our eyes. (b) Double-slit interference pattern for water waves are nearly identical to that for light. Wave action is greatest in regions of constructive interference and least in regions of destructive interference. (c) When light that has passed through double slits falls on a screen, we see a pattern such as this.



Theoretical Constructive and Destructive Wave Interference: The amplitudes of waves add together. (a) Pure constructive interference is obtained when identical waves are in phase. (b) Pure destructive interference occurs when identical waves are exactly out of phase (shifted by half a wavelength).

The pattern that results from double-slit diffraction is not random, although it may seem that way. Each slit is a different distance from a given point on the wall behind it. For each different distance, a different number of wavelengths fit into that path. The waves all start out in phase (matching crest-to-crest), but depending on the distance of the point on the wall from the slit, they could be in phase at that point and interfere constructively, or they could end up out of phase and interfere with each other destructively.

Diffraction Gratings: X-Ray, Grating, Reflection

Diffraction grating has periodic structure that splits and diffracts light into several beams travelling in different directions.

learning objectives

- Describe function of the diffraction grating

Diffraction Grating

A diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams travelling in different directions. The directions of these beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element. Because of this, gratings are often used in monochromators, spectrometers, wavelength division multiplexing devices, optical pulse compressing devices, and many other optical instruments.

A photographic slide with a fine pattern of purple lines forms a complex grating. For practical applications, gratings generally have ridges or rulings on their surface rather than dark lines. Such gratings can be either transmissive or reflective. Gratings which modulate the phase rather than the amplitude of the incident light are also produced, frequently using holography.

Ordinary pressed CD and DVD media are every-day examples of diffraction gratings and can be used to demonstrate the effect by reflecting sunlight off them onto a white wall. (see). This is a side effect of their manufacture, as one surface of a CD has many small pits in the plastic, arranged in a spiral; that surface has a thin layer of metal applied to make the pits more visible. The structure of a DVD is optically similar, although it may have more than one pitted surface, and all pitted surfaces are inside the disc. In a standard pressed vinyl record when viewed from a low angle perpendicular to the grooves, one can see a similar, but less defined effect to that in a CD/DVD. This is due to viewing angle (less than the critical angle of reflection of the black vinyl) and the path of the light being reflected due to being changed by the grooves, leaving a rainbow relief pattern behind.

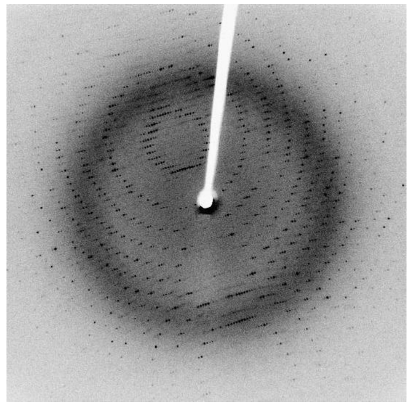
Readable Surface of a CD: The readable surface of a Compact Disc includes a spiral track wound tightly enough to cause light to diffract into a full visible spectrum.

Some bird feathers use natural diffraction grating which produce constructive interference, giving the feathers an iridescent effect. Iridescence is the effect where surfaces seem to change color when the angle of illumination is changed. An opal is another example of diffraction grating that reflects the light into different colors.

X-Ray Diffraction

X-ray crystallography is a method of determining the atomic and molecular structure of a crystal, in which the crystalline atoms cause a beam of X-rays to diffract into many specific directions. By measuring the angles and intensities of these diffracted beams, a crystallographer can produce a three-dimensional picture of the density of electrons within the crystal. From this electron density, the mean positions of the atoms in the crystal can be determined, as well as their chemical bonds, their disorder and various other information.

In an X-ray diffraction measurement, a crystal is mounted on a goniometer and gradually rotated while being bombarded with X-rays, producing a diffraction pattern of regularly spaced spots known as reflections (see). The two-dimensional images taken at different rotations are converted into a three-dimensional model of the density of electrons within the crystal using the mathematical method of Fourier transforms, combined with chemical data known for the sample.



Reflections in Diffraction Patterns: Each dot, called a reflection, in this diffraction pattern forms from the constructive interference of scattered X-rays passing through a crystal. The data can be used to determine the crystalline structure.

Single Slit Diffraction

Single slit diffraction is the phenomenon that occurs when waves pass through a narrow gap and bend, forming an interference pattern.

learning objectives

- Formulate the Huygens's Principle

Diffraction

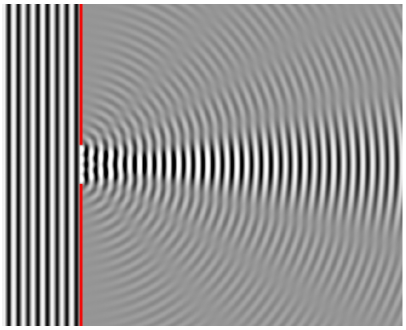
As we explained in a previous atom, diffraction is defined as the bending of a wave around the edges of an opening or obstacle. Diffraction is a phenomenon all wave types can experience. It is explained by the *Huygens-Fresnel Principle*, and the principal of superposition of waves. The former states that every point on a wavefront is a source of wavelets. These wavelets spread out in the forward direction, at the same speed as the source wave. The new wavefront is a line tangent to all of the wavelets. The superposition principle states that at any point, the net result of multiple stimuli is the sum of all stimuli.

Single Slit Diffraction

In single slit diffraction, the diffraction pattern is determined by the wavelength and by the length of the slit. Figure 1 shows a visualization of this pattern. This is the most simplistic way of using the Huygens-Fresnel Principle, which was covered in a previous atom, and applying it to slit diffraction. But what happens when the slit is NOT the exact (or close to exact) length of a single wave?

Single Slit Diffraction – One Wavelength: Visualization of single slit diffraction when the slit is equal to one wavelength.

A slit that is wider than a single wave will produce interference -like effects downstream from the slit. It is easier to understand by thinking of the slit not as a long slit, but as a number of point sources spaced evenly across the width of the slit. This can be seen in Figure 2.



Single Slit Diffraction – Four Wavelengths: This figure shows single slit diffraction, but the slit is the length of 4 wavelengths.

To examine this effect better, lets consider a single monochromatic wavelength. This will produce a wavefront that is all in the same phase. Downstream from the slit, the light at any given point is made up of contributions from each of these point sources. The resulting phase differences are caused by the different in path lengths that the contributing portions of the rays traveled from the slit.

The variation in wave intensity can be mathematically modeled. From the center of the slit, the diffracting waves propagate radially. The angle of the minimum intensity (θ_{min}) can be related to wavelength (λ) and the slit's width (d) such that:

$$\mathrm{d} \sin \theta_{\min} = \lambda \tag{6.2.2}$$

The intensity (I) of waves at any angle can also be calculated as a relation to slit width, wavelength and intensity of the original waves before passing through the slit:

$$\mathrm{I}(\theta) = \mathrm{I}_0 \left(\frac{\sin(\pi \mathrm{x})}{\pi \mathrm{x}} \right)^2 \tag{6.2.3}$$

where x is equal to:

$$\frac{\mathrm{d}}{\lambda} \sin \theta \tag{6.2.4}$$

The Rayleigh Criterion

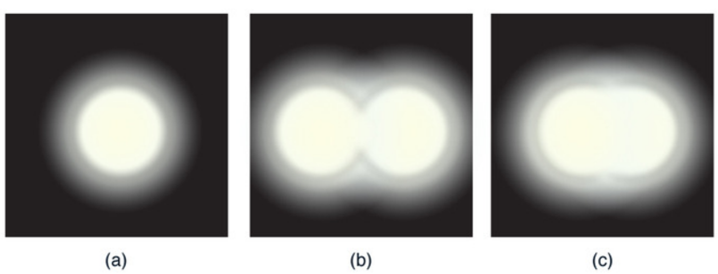
The Rayleigh criterion determines the separation angle between two light sources which are distinguishable from each other.

learning objectives

- Explain meaning of the Rayleigh criterion

Resolution Limits

Along with the diffraction effects that we have discussed in previous atoms, diffraction also limits the detail that we can obtain in images. shows three different circumstances of resolution limits due to diffraction:



Resolution Limits: (a) Monochromatic light passed through a small circular aperture produces this diffraction pattern. (b) Two point light sources that are close to one another produce overlapping images because of diffraction. (c) If they are closer together, they cannot be resolved or distinguished.

- (a) shows a light passing through a small circular aperture. You do not see a sharp circular outline, but a spot with fuzzy edges. This is due to diffraction similar to that through a single slit.
- (b) shows two point sources close together, producing overlapping images. Due to the diffraction, you can just barely distinguish between the two point sources.
- (c) shows two point sources which are so close together that you can no longer distinguish between them.

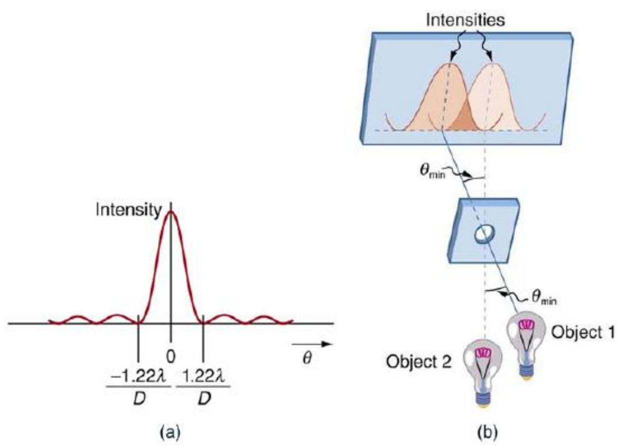
This effect can be seen with light passing through small apertures or larger apertures. This same effect happens when light passes through our pupils, and this is why the human eye has limited acuity.

Rayleigh Criterion

In the 19th century, Lord Rayleigh invented a criteria for determining when two light sources were distinguishable from each other, or resolved. According to the criteria, two point sources are considered just resolved (just distinguishable enough from each other to recognize two sources) if the center of the diffraction pattern of one is directly overlapped by the first minimum of the diffraction pattern of the other. If the distance is greater between these points, the sources are well resolved (i.e., they are easy to distingiush from each other). If the distance is smaller, they are not resolved (i.e., they cannot be distinguished from each other). The equation to determine this is:

$$\theta = 1.22 \frac{\lambda}{\mathrm{D}} \tag{6.2.5}$$

θ – angle the objects are separated by, in radian λ – wavelength of light D – aperture diameter. shows this concept visually. This equation also gives the angular spreading of a source of light having a diameter D.



Rayleigh Criterion: (a) This is a graph of intensity of the diffraction pattern for a circular aperture. Note that, similar to a single slit, the central maximum is wider and brighter than those to the sides. (b) Two point objects produce overlapping diffraction patterns. Shown here is the Rayleigh criterion for being just resolvable. The central maximum of one pattern lies on the first minimum of the other.

Key Points

- Diffraction is the concept that is explained using Huygens's Principle, and is defined as the bending of a wave around the edges of an opening or an obstacle.
- This principle can be used to define reflection, as shown in the figure. It can also be used to explain refraction and interference. Anything that experiences this phenomenon is a wave. By applying this theory to light passing through a slit, we can prove it is a wave.
- The principle can be shown with the equation below: s=vt s – distance v – propagation speed t – time Each point on the wavefront emits a wave at speed, v. The emitted waves are semicircular, and occur at t, time later. The new wavefront is tangent to the wavelets.
- The wave characteristics of light cause the light to pass through the slits and interfere with each other, producing the light and dark areas on the wall behind the slits. The light that appears on the wall behind the slits is partially absorbed by the wall, a characteristic of a particle.

- Constructive interference occurs when waves interfere with each other crest-to-crest and the waves are exactly in phase with each other. Destructive interference occurs when waves interfere with each other crest-to-trough (peak-to-valley) and are exactly out of phase with each other.
- Each point on the wall has a different distance to each slit; a different number of wavelengths fit in those two paths. If the two path lengths differ by a half a wavelength, the waves will interfere destructively. If the path length differs by a whole wavelength the waves interfere constructively.
- The directions of the diffracted beams depend on the spacing of the grating and the wavelength of the light so that the grating acts as the dispersive element.
- Gratings are commonly used in monochromators, spectrometers, wavelength division multiplexing devices, optical pulse compressing devices, and other optical instruments.
- Diffraction of X-ray is used in crystallography to produce the three-dimensional picture of the density of electrons within the crystal.
- The Huygens's Principle states that every point on a wavefront is a source of wavelets. These wavelets spread out in the forward direction, at the same speed as the source wave. The new wavefront is a line tangent to all of the wavelets.
- If a slit is longer than a single wavelength, think of it instead as a number of point sources spaced evenly across the width of the slit.
- Downstream from a slit that is longer than a single wavelength, the light at any given point is made up of contributions from each of these point sources. The resulting phase differences are caused by the different in path lengths that the contributing portions of the rays traveled from the slit.
- Diffraction plays a large part in the resolution at which we are able to see things. There is a point where two light sources can be so close to each other that we cannot distinguish them apart.
- When two light sources are close to each other, they can be: unresolved (i.e., not able to distinguish one from the other), just resolved (i.e., only able to distinguish them apart from each other), and a little well resolved (i.e., easy to tell apart from one another).
- In order for two light sources to be just resolved, the center of one diffraction pattern must directly overlap with the first minimum of the other diffraction pattern.

Key Terms

- **diffraction**: The bending of a wave around the edges of an opening or an obstacle.
- **constructive interference**: Occurs when waves interfere with each other crest to crest and the waves are exactly in phase with each other.
- **destructive interference**: Occurs when waves interfere with each other crest to trough (peak to valley) and are exactly out of phase with each other.
- **interference**: An effect caused by the superposition of two systems of waves, such as a distortion on a broadcast signal due to atmospheric or other effects.
- **iridescence**: The condition or state of being iridescent; exhibition of colors like those of the rainbow; a prismatic play of color.
- **diffraction**: The bending of a wave around the edges of an opening or an obstacle.
- **monochromatic**: Describes a beam of light with a single wavelength (i.e., of one specific color or frequency).
- **resolution**: The degree of fineness with which an image can be recorded or produced, often expressed as the number of pixels per unit of length (typically an inch).

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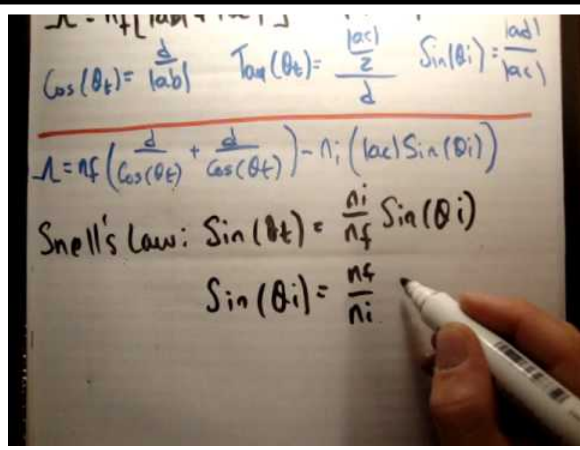
6.3: Further Topics

learning objectives

- Describe process that leads to the thin film interference

Thin Film Interference

This is a phenomenon that occurs when incident rays reflected by the upper and lower boundaries of a thin film interfere with one another and form a new wave. A material is considered to be a thin film if its thickness is in the sub-nanometer to micron range, *e.g.* a soap bubble. Studying the new wave can shed light on properties of the film, such as thickness or refractive index. Interference effects are most prominent when the light interacts with something that has a size similar to its own wavelength. The thickness of a thin film is a few times smaller than the wavelength of the light, λ. Color is indirectly associated with wavelength. The interference ratio of wavelength to size of the object causes the appearance of colors.



Thin Film Interference: In this video I continue with my tutorials on Electromagnetism to Optics which is pitched at university undergraduate level. I have intended for a long time to record videos which describe the transition made from classical electromagnetism to optics. In many respects these videos will cover 'wave' optics. I devote much time to discussing the complex exponential representation of waves, Maxwell's Equations, the wave equation etc.Specifically here, I derive the formula for the optical path difference and the phase difference for a 'wave' of light propagating through a thin film. This expression can be used for anti reflective coatings. The phase difference is the product of the optical path differene and the wave vector k.I hope it's of use!! Thank you for watching and I hope that this matches your requirements.

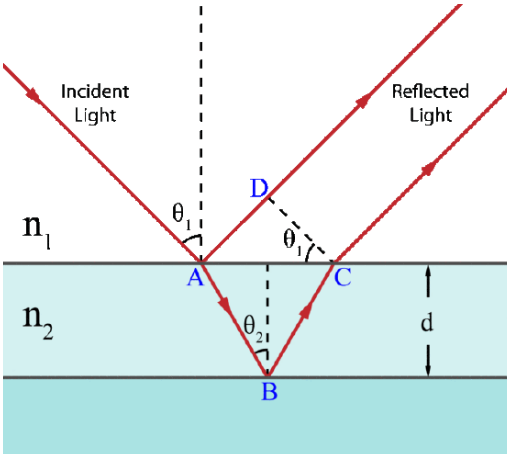
Thin Film Interference in Oil: Thin film interference can be seen in this oil slick.

Examples of Thin Film Interference

You have probably witnessed thin film interference in your every day life and just not realized it. Whenever you see the bright, rainbow like colors in oil floating in water, shown in, this is thin film interference. The colors that appear in bubbles that kids play with are also a result of thin film interference. Thin film interference can have commercial applications, such as anti- reflection coatings and optical filters.

How it Works

shows a diagram of how thin film interference works. As light strikes the surface of a film it is either transmitted or reflected at the upper surface. Light that is transmitted reaches the bottom surface and may once again be transmitted or reflected. The light reflected from the upper and lower surfaces will interfere. The degree of constructive or destructive interference between the two light waves is dependent upon the difference in their phase. This difference is dependent upon the thickness of the film layer, the refractive index of the film, and the angle of incidence of the original wave on the film. Additionally, a phase shift of 180° or ππ radians may be introduced upon reflection at a boundary depending on the refractive indices of the materials on either side said boundary. This phase shift occurs if the refractive index of the medium the light is travelling through is less than the refractive index of the material it is striking. In other words, if n1<n2n1<n2and the light is travelling from material 1 to material 2, then a phase shift will occur upon reflection. The pattern of light that results from this interference can appear either as light and dark bands or as colorful bands depending upon the source of the incident light.



Light on a Thin Film: Light incident on a thin film. Demonstration of the optical path length difference for light reflected from the upper and lower boundaries.

Interference will be constructive if the optical path difference is equal to an integer multiple of the wavelength of light:

$$2 \mathrm{n}_2 \mathrm{d} \cos(\theta_2) = \mathrm{m}\lambda \tag{6.3.1}$$

where mm is the integer, dd is the thickness of the film, and λλ is the wavelength of light. However, this condition may change if phase shifts occur upon reflection.

Polarization By Passing Light Through Polarizers

Polarization is the attribute that wave oscillations have a definite direction relative to the direction of propagation of the wave.

learning objectives

- Discuss polarization of electromagnetic waves

Definition of Polarization

As we discusses in previous atoms, light waves are a type of electromagnetic waves, in the visible spectrum. These electromagnetic (EM) waves are transverse waves. Figure 1 demonstrates that a transverse wave is one oscillates perpendicular to the direction of the energy transfer. If the wave is traveling from left to right, it is oscillating up and down. Polarization is the property of waves that allow them to oscillate in more than one direction, but that direction is relative to that of the direction the wave is traveling in. For an EM wave, the direction of polarization is the direction parallel to the electric field. In Figure 2 you can see that the EM and magnetic fields are perpendicular to the path of travel. Since the direction of polarization is parallel to the electric field, you can consider the blue arrows to be the direction of polarization.

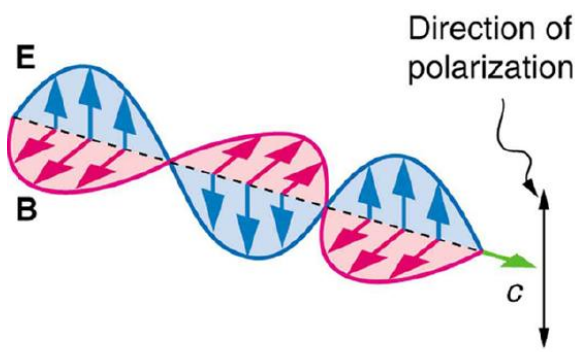


Figure 2: An EM wave, such as light, is a transverse wave. The electric and magnetic fields are perpendicular to the direction of propagation.

Figure 1: Transverse Waves

How it Works

Now, to examine the effects of passing light through a polarizer, lets look at Figure 3. shows a stationary vertical slot, which will act as a polarizer, and two waves traveling in the same direction, but one is oscillating vertically,a, (and therefore vertically polarized), and the other, b, horizontally. What happens to these waves as they pass through the polarizer?When wave a, the vertically oscillating wave is passed through the vertically polarized slot, nothing happens. The wave passes through untouched or manipulated. When wave b, the horizontally oscillating wave is passed through, the vertically polarized slot blocks the wave, and it is not passed through at all. Now that we understand the concept of polarization, and how it works, how can we apply this to make it useful? Look at Figure 4. The image on the left is full of glare, which makes it hard to see what we are looking at. The image on the right was taken with a polarized lens, so you only see the image, and none of the annoying glare. How this works is diagramed in Figure 5. Many light sources are unpolarized, and are comprised of many waves in all possible directions. Polarized lenses only allow one direction of light to pass through, minimizing the unwanted aspects of the light rays, such as glare. Simply, passing light through a polarized material changes the intensity of the light.

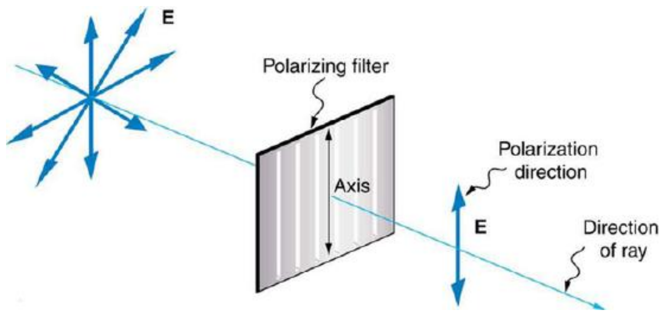


Figure 5: A polarizing filter has a polarization axis that acts as a slit passing through electric fields parallel to its direction. The direction of polarization of an EM wave is defined to be the direction of its electric field.

Figure 4: These two photographs of a river show the effect of a polarizing filter in reducing glare in light reflected from the surface of water. Part (b) of this figure was taken with a polarizing filter and part (a) was not. As a result, the reflection of clouds and sky observed in part (a) is not observed in part (b). Polarizing sunglasses are particularly useful on snow and water. (credit: Amithshs, Wikimedia Commons)

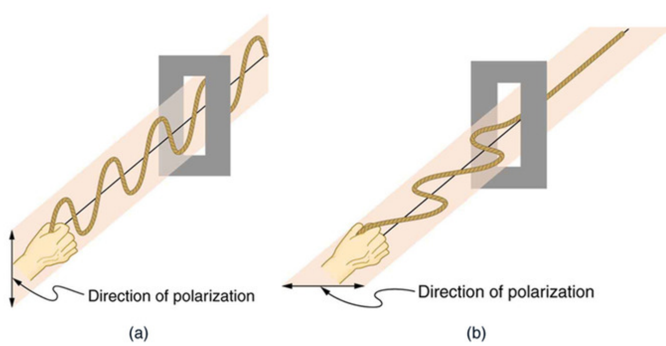


Figure 3: Example of passing light through a polarizer

Intensity

Lets call the angle between the direction of polarization and the axis of the polarization filter θ. The original intensity of the light before it is passed through a filter is denoted by I_0. In order to find the new intensity of light after traveling through the material is shown by the following equation:

$$I = I_0 \cos 2\theta \tag{6.3.2}$$

If you pass light through two polarizing filters, you will get varied effects of polarization. If the two filters are oriented exactly perpendicular to each other, no light will pass through at all. If they are exactly parallel to each other, there will be no additional affect from the additional filter.

Polarization By Scattering and Reflecting

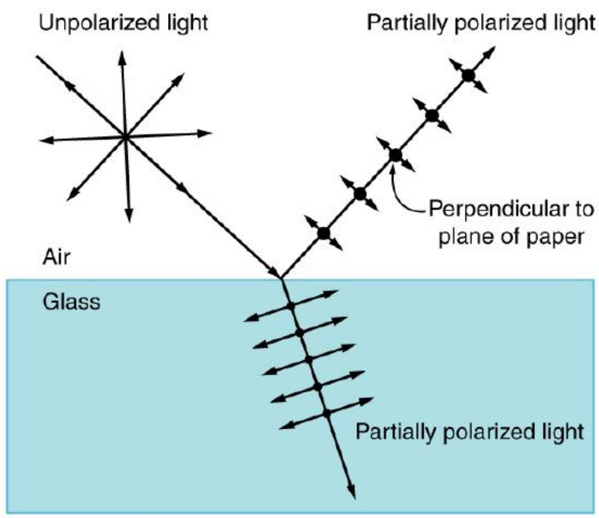
Unpolarized light can be polarized artificially, as well as by natural phenomenon like reflection and scattering.

learning objectives

- Calculate angle of reflection of complete polarization from indices of refraction

Polarization by Reflection

In the previous atom we discussed how polarized lenses work. In the case of polarized sunglasses, for example, when you look through them, reflected light is not entirely filtered out; reflected light can be slightly polarized by the reflection process (as shown in). Most light sources produce unpolarized light. When light hits a reflective surface, the vertically polarized aspects of that light are refracted at that surface. The reflected light is more horizontally polarized. To better remember this, we can think of light as an arrow and the reflective surface as a target. If the arrow hits the target perpendicularly (vertically polarized), it is going to stick in the target (be refracted into the surface). If the arrow hits the target on its side (horizontally polarized) then it will bounce right off (be reflected).



Polarization by Reflection: Unpolarized light has equal amounts of vertical and horizontal polarization. After interaction with a surface, the vertical components are preferentially absorbed or refracted, leaving the reflected light more horizontally polarized. This is akin to arrows striking on their sides bouncing off, whereas arrows striking on their tips go into the surface.

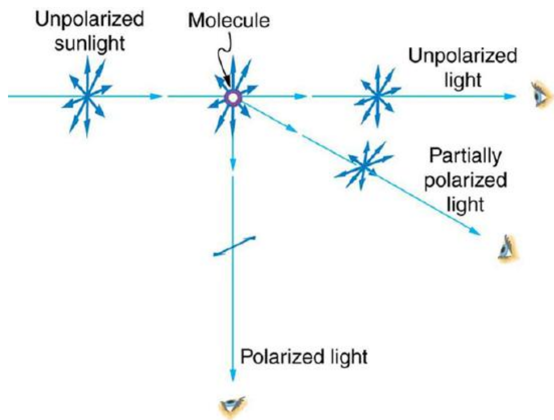
Since the light is split into two, and part of it is refracted, the amount of polarization to the reflected light depends on the index of refraction of the reflective surface. We can use the following equation to determine the angle of reflection at which light will be completely polarized:

$$\tan\theta_b = \frac{n_2}{n_1} \tag{6.3.3}$$

where: θ_b = angle of reflection of complete polarization (also known as Brewster's angle); n_1 = index of refraction of medium in which reflected light will travel; and n_2 = index of refraction of medium by which light is reflected.

Polarization by Scattering

Just as unpolarized light can be partially polarized by reflecting, it can also be polarized by scattering (also known as Rayleigh scattering; illustrated in). Since light waves are electromagnetic (EM) waves (and EM waves are transverse waves) they will vibrate the electrons of air molecules perpendicular to the direction in which they are traveling. The electrons then produce radiation (acting like small antennae) that is polarized perpendicular to the direction of the ray. The light parallel to the original ray has no polarization. The light perpendicular to the original ray is completely polarized. In all other directions, the light scattered by air will be partially polarized.



Polarization by Scattering: Also known as Rayleigh scattering. Unpolarized light scattering from air molecules shakes their electrons perpendicular to the direction of the original ray. The scattered light therefore has a polarization perpendicular to the original direction and none parallel to the original direction.

Scattering of Light by the Atmosphere

Rayleigh scattering describes the air's gas molecules scattering light as it enters the atmosphere; it also describes why the sky is blue.

learning objectives

- Describe wave-particle relationship that leads to Rayleigh scattering and apply it to explain common phenomena

Rayleigh Scattering

Rayleigh scattering is the elastic scattering of waves by particles that are much smaller than the wavelengths of those waves. The particles that scatter the light also need to have a refractive index close to 1. This law applies to all electromagnetic radiation, but in this atom we are going to focus specifically on why the atmosphere scatters the visible spectrum of electromagnetic waves, also known as visible light. In this case, the light is scattered by the gas molecules of the atmosphere, and the refractive index of air is 1.

Rayleigh scattering is due to the polarizability of an individual molecule. This polarity describes how much the electric charges in the molecule will vibrate in an electric field. The formula to calculate the intensity of the scattering for a single particle is as follows:

$$\mathrm{I} = \mathrm{I}_0 \frac{8\pi^4\alpha^2}{\lambda^4 \mathrm{R}^2}\left(1+\cos^2\theta\right) \tag{6.3.4}$$

where I is the resulting intensity, I_0 is the original intensity, α is the polarizability, λ is the wavelength, R is the distance to the particle, and θ is the scattering angle.

While you will probably not need to use this formula, it is important to understand that scattering has a strong dependence on wavelength. From the formula, we can see that a shorter wavelength will be scattered more strongly than a longer one.(The longer the wavelength, the larger the denominator, and from algebra we know that a larger denominator in a fraction means a smaller number.)

Why is the Sky Blue?

As we just learned, light scattering is inversely proportional to the fourth power of the light wavelength. So, the shorter the wavelength, the more it will get scattered. Since green and blue have relatively short wavelengths, you see a mixture of these colors in the sky, and the sky appears to be blue. When you look closer and closer to the sun, the light is not being scattered because it is approaching a 90-degree angle with the scattering particles. Since the light is being scattered less and less, you see the longer wavelengths, like red and yellow. This is why the sun appears to be a light yellow color.

Why are Sunsets Colorful?

shows a sunset. We know why the sky is blue, but why are there all those colors in a sunset? The reddening that occurs near the horizon is because the light has to pass through a significantly higher volume of air than when the sun is high in the sky. This increases the Rayleigh scattering effect and removes all blue light from the direct path of the observer. The remaining unscattered light is of longer wavelengths and so appears orange.

Sunset: A gradient of colors in the sky during sunset

Dispersion of the Visible Spectrum

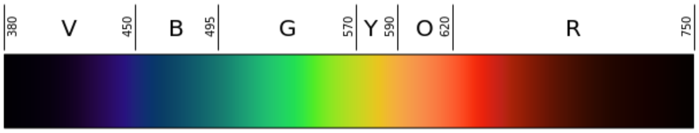
Dispersion is the spreading of white light into its full spectrum of wavelengths; this phenomenon can be observed in prisms and rainbows.

learning objectives

- Describe process of dispersion

The Visible Spectrum

Within the electromagnetic spectrum, there is only a portion that is visible to the human eye. Visible light is the range of wavelengths of electromagnetic radiation that humans can see. For a typical human eye, this ranges from 390 nm to 750 nm. shows this range and the colors associated with it:



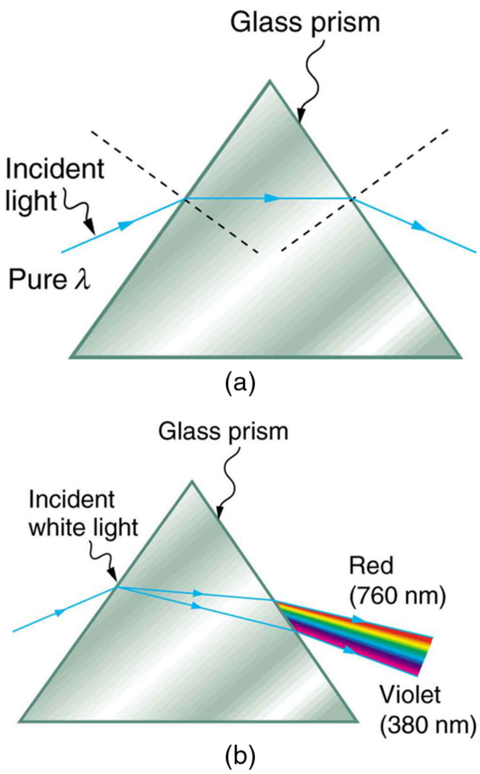
The Visible Spectrum: Visible Spectrum, represented linearly

- Violet: 380-450 nm
- Blue: 450-495 nm
- Green: 495-570 nm
- Yellow: 570-590 nm
- Orange: 590-620 nm
- Red: 620-750 nm

As you can see from, these are the colors of a rainbow and it is no coincidence.

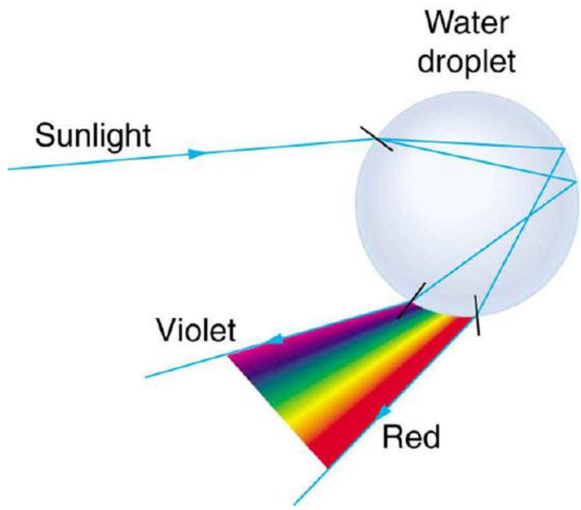
Dispersion

Dispersion is the spreading of white light into its full spectrum of wavelengths. How does this happen? The index of refraction is different for every medium that light travels through, as we learned in previous atoms. When a light ray enters a medium with a different index of refraction, the light is dispersed, as shown in with a prism. When white light enters the prism, it spreads. Since the index of refraction varies with wavelength, the light refracts at different angles as it exits, causing the exiting light rays to appear as a rainbow, or as a sequence of decreasing wavelengths, from red to violet.



Light and a Glass Prism: (a) A pure wavelength of light falls onto a prism and is refracted at both surfaces. (b) White light is dispersed by the prism (shown exaggerated). Since the index of refraction varies with wavelength, the angles of refraction vary with wavelength. A sequence of red to violet is produced, because the index of refraction increases steadily with decreasing wavelength.

This same principle can be applied to rainbows. Refer to. Rainbows are not only caused by refraction, like prisms, but also reflection. Light enters a drop of water and is reflected from the back of the droplet. The light is refracted once as it enters the drop, and again as is exits the drop. In water, the refractive index varies with wavelength, so the light is dispersed.



Light and a Water Droplet: Part of the light falling on this water drop enters and is reflected from the back of the drop. This light is refracted and dispersed both as it enters and as it leaves the drop.

Key Points

- When the incident light reaches the thin film, it is partially reflected and passed through to the bottom layer of the film. The difference in refractive indices of the air and film causes the light to change direction and interfere with the reflected portion of the ray when it emerges.
- This interference can be constructive, producing bright colors, or destructive, producing darker colors.
- Interference will be constructive if the optical path difference is equal to an integer multiple of the wavelength of light.
- The direction of polarization is parallel to the direction of the electric field associated with an electromagnetic wave, which includes light waves.
- By employing the polarization properties of waves, companies like Polariod how been able to produce materials that filter out unwanted waves of light, and minimize light intensity.
- Polarization materials can be oriented at different angles to produce different effects. The new intensity of light after passing through these materials can be found using the following formula: $I=I_0\cos 2\theta$.
- When unpolarized light hits a reflective surface, the vertically polarized aspects are refracted into the surface. The horizontally polarized aspects are reflected off the surface and the light is now perceived as partially polarized.
- When light is reflected, there is an angle at which this light is completely polarized. This is called Brewster's angle, after the Scottish physicst who discovered the law.
- Unpolarized light can also become polarized when it is scattered in air (also known as Rayleigh scattering). This occurs due to the fact that the EM waves cause the electron in air to vibrate, producing radiation and causing polarization of the light.
- The phenomenon of light scattering is called Rayleigh scattering; it can happen to any electromagnetic waves. It only occurs when waves encounter particles that are much smaller than the wavelengths of the waves.
- The amount that light is scattered is inversely proportional to the fourth power of the light wavelength. For this reason, shorter-wavelength light like greens and blues scatter more easily than longer wavelengths like yellows and reds.
- As you look closer to the sky's light source, the sun, the light is scattered less and less because the angle between the sun and the scattering particles approaches 90 degrees. This is why the sun has a yellowish color when we look at it from Earth while the rest of the sky appears blue.
- In outer space, where there is no atmosphere and therefore no particles to scatter the light, the sky appears black and the sun appears white.
- During a sunset, the light must pass through an increased volume of air. This increases the scattering effect, causing the light in the direct path of the observer to appear orange rather than blue.
- Dispersion is a side effect of the law of refraction. As refraction angles depend on wavelength, when light enters a medium with a different index of refraction, it can be dispersed, like a prism.
- The dispersion of white light can often cause the refracted light to be observed is in order of either increasing or decreasing wavelength, causing a rainbow effect.
- As you can see from the visible spectrum, there are some colors that the brain perceives that are not included. This is because some colors are a mixture of different wavelengths, like pink and magenta.

Key Terms

- **incident ray**: The ray of light that strikes the surface.
- **interference**: An effect caused by the superposition of two systems of waves, such as a distortion on a broadcast signal due to atmospheric or other effects.
- **wavelength**: The length of a single cycle of a wave, as measured by the distance between one peak or trough of a wave and the next; it is often designated in physics as λ, and corresponds to the velocity of the wave divided by its frequency.
- **oscillate**: To swing back and forth, especially if with a regular rhythm.
- **index of refraction**: For a material, the ratio of the speed of light in vacuum to that in the material.
- **polarization**: The production of polarized light; the direction in which the electric field of an electromagnetic wave points.
- **electromagnetic radiation**: radiation (quantized as photons) consisting of oscillating electric and magnetic fields oriented perpendicularly to each other, moving through space
- **polarizability**: The relative tendency of a system of electric charges to become polarized in the presence of an external electric field
- **refraction**: Changing of a light ray's direction when it passes through variations in matter.
- **reflection**: the property of a propagated wave being thrown back from a surface (such as a mirror)
- **dispersion**: The separation of visible light by refraction or diffraction.

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6.4: Applications of Wave Optics

learning objectives

- Compare optical and electron microscopy

Microscopes are used to view objects that cannot be seen with the naked eye. In this section we will discuss both optical and electron microscopy.

Optical Microscopy

You have probably used an optical microscope in a high school science class. In optical microscopy, light reflected from an object passes through the microscope's lenses; this magnifies the light. The resultant, magnified image is then seen by the eye. Although this type of microscopy has many limitations, there are several techniques that use properties of light and optics to enhance the magnified image:

- Bright field: This technique increases the contrast by illuminating the surface on which the objects sit from below.
- Oblique illumination: This technique illuminates the object from the side, giving it a three-dimensional appearance and highlighting features that would otherwise not be visible.
- Dark field: This technique is good for improving the contrast of transparent objects. A carefully aligned light source minimizes the un-scattered light entering the object plane and so only collects the light that is scattered by the object itself.
- Dispersion staining: This results in a colored image of a colorless object; it does not actually require that the object be stained.
- Phase contrast: This uses the refractive index of an object to show differences in optical density as a difference in contrast. provides a demonstration of this technique.

Electron Microscopy

Electron microscopes use electron beams to achieve higher resolutions than are possible in optical microscopy. Two kinds of electron microscopes are:

- Transmission electron microscope (TEM): The TEM sends an electron beam through a thin slice of a specimen. The electron interacts with the specimen and is then transmitted onto photographic paper or a screen. Since electron beams have a much smaller wavelength than traditional light, the resolution of the resulting image is much higher.
- Scanning electron microscope (SEM): The SEM shows details on the surface of a specimen and produces a three-dimensional view by scanning the specimen. shows an SEM image of pollen.

The Spectrometer

A spectrometer uses properties of light to identify atoms by measuring wavelength and frequency, which are functions of radiated energy.

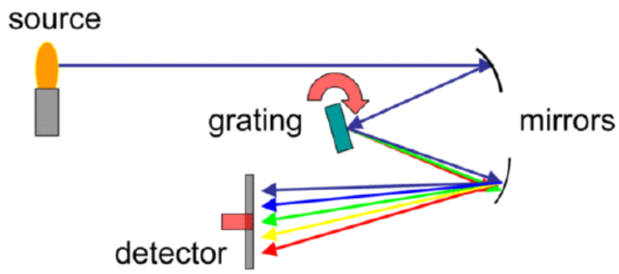
learning objectives

- Compare design and function of early and modern spectrometers

The Spectrometer

A spectrometer is an instrument used to intensely measure light over a specific portion of the electromagnetic spectrum, to identify materials. The instrument produces lines, much like those produced from diffraction grating as covered in a previous atom, and then measures the wavelengths and intensities of those lines.

shows a diagram of how a spectrometer works. The source is placed in front of a mirror, which reflects the light emitted from that object onto a diffraction grating. This grating then disperses the emitted light to anther mirror which spreads the different resultant wavelengths and reflects them onto a detector which records the findings. This type of instrument is used in spectroscopy.



Spectrometer Diagram: This diagram shows the light pathways in a spectrometer.

Spectroscopy

Spectroscopy studies the interaction between matter and radiated energy. This radiated energy is a function of wavelength and frequency. Every type of atom has its own frequency. When the spectrometer produces a reading, the observer can then use spectroscopy to identify the atoms and therefore molecules that make up that object.

Spectroscopes

Spectroscopes are used in a variety of fields, such as astronomy and chemistry. They use a diffraction grating, movable slit, and a photodetector. All of these elements are controlled by a computer, which records the findings. A material is heated to incandescence and it emits a light that is characteristic of its atomic makeup. Each atom has its own spectroscopic 'fingerprint'. In you can see a very simple spectroscope based on a prism. As another example, Sodium produces a double yellow band.

A simple spectroscope: A very simple spectroscope based on a prism

The Michelson Interferometer

The Michelson interferometer is the most common configuration for optical interferometry.

learning objectives

- Explain how the Michelson interferometer works

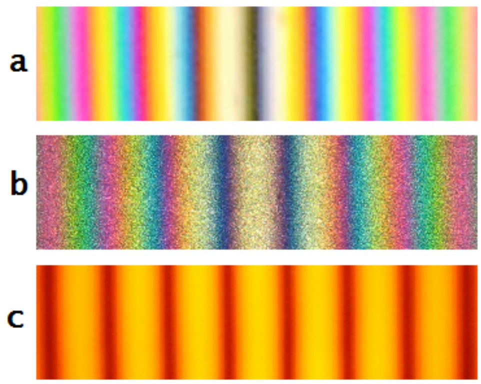
Interferometry

Before we can discuss the Michelson Interferometer, it is important we first understand interferometry—which refers to techniques that use superimposed waves to extract information about the waves. More simply, it uses the interference these waves experience to make accurate measurements of the waves. It is used in many areas of science, such as astronomy, engineering, oceanography, physics, and fiber optics.

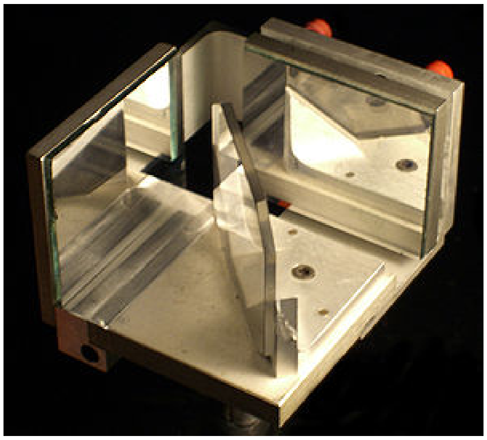
Popular applications of interferometry in industry include the measurement of small displacements, refractive index changes, and surface irregularities. As shown in previous atoms, when two waves with the same frequency combine, the resulting pattern is determined by the phase difference between the two. Constructive interference occurs when the waves are in phase, and destructive interference occurs when they are out of phase. Interferometry uses this principle to combine waves and study the resulting wave in order to obtain information about the original state of the waves.

The Michelson Interferometer

The most common tool in interferometry, the Michelson Interferometer, shown in Figure 1, was invented by Albert Abraham Michelson, the first American to win a Nobel Prize for science. The interferometer works by splitting a beam of light into two paths, bouncing them back and then recombining them to create an interference pattern. To create interference fringes on a detector (see Figure 2), the paths may be different lengths or composed of different materials.



Fringes in a Michelson Interferometer: Colored and monochromatic fringes in a Michelson interferometer: (a) White light fringes where the two beams differ in the number of phase inversions; (b) White light fringes where the two beams have experienced the same number of phase inversions; and (c) Fringe pattern using monochromatic light (sodium D lines).



Michelson Interferometer: A Michelson Interferometer.

Figure 3 shows a diagram of how a Michelson Interferometer works. M_1 and M_2 are two highly polished mirrors, S is the light source, M is a half silvered mirror that acts as a beam splitter when the light hits the surface, and C is a point on M that is partially reflective. When the beam S hits this point on M it is split into two beams. One beam is reflected in the direction of A and the other is transmitted through the surface of M to the point B. A and B are both points on the highly polished (and therefore reflective) mirrors M_1 and M_2. When the beams hit these points, they are then reflected back to point C', where they recombine to produce an interference pattern. At point E, the interference pattern produced at point C' is visible to an observer.

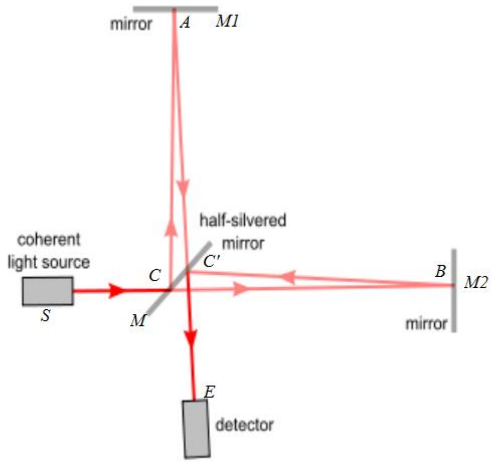


Figure 3: This diagram of a Michelson Interferometer shows the path that the light waves travels in the instrument.

Applications

The Michelson Interferometer has been used for the detection of gravitational waves, as a tunable narrow band filter, and as the core of Fourier transform spectroscopy. It has played an important role in studies of the upper atmosphere, revealing temperatures and winds (employing both space-borne and ground-based instruments) by measuring the Doppler widths and shifts in the spectra of airglow and aurora. The best known application of the Michelson Interferometer is the Michelson-Morley experiment—a failed attempt to demonstrate the effect of the hypothetical ” aether wind” on the speed of light. Their experiment left theories of light based on the existence of a luminiferous aether without experimental support, and served ultimately as an inspiration for special relativity.

LCDs

Liquid crystal displays use liquid crystals which do not emit light, but use the light modulating properties of the crystals.

learning objectives

- Explain how liquid crystal displays produce images and discuss their benefits and deficiencies

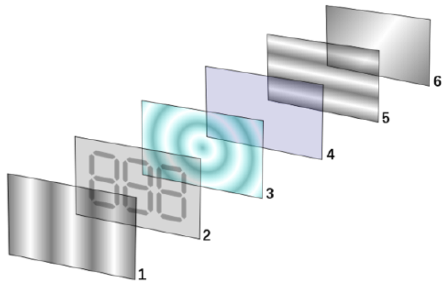
LCDs

LCD stands for a liquid crystal display. The liquid crystals themselves do not emit light, but the display uses the light modulating properties of the crystals. LCDs can be used to display arbitrary images, such as in a computer monitor or television, by using a large number of very small pixels, or they can be used to display fixed images, like a digital clock, such as in.

Digital Clock: A digital clock which uses LCD to either hide or display fixed images.

Unlike the newer cathode ray tube (CRT) and plasma displays, LCDS do not use phosphors. For this reason they do not suffer image burn-in. They do however suffer image persistence. Image burn-in occurs when an image is displayed so many times, or for so long, that an outline of image can be seen even when the display is turned off. Image persistence is similar, but the outline fades away shortly after the display is turned off and is not permanent.

LCD displays are made up of numerous layers. A typical layer is diagrammed in. Each pixel of an LCD consists of a layer of molecules aligned between two transparent electrodes and two polarizing films, and the actual liquid crystals are between these polarizing filters. The light passes through the first filter, and is blocked by the second. The electrodes are used to align the crystals in a particular direction, which produces the image seen on the screen. The crystals do not emit any light, but rather give the light a specific shape to be emitted in.



Layers of LCD Displays: Polarizing filter film with a vertical axis to polarize light as it enters.Glass substrate with ITO electrodes. The shapes of these electrodes will determine the shapes that will appear when the LCD is turned on. Vertical ridges etched on the surface are smooth.Twisted nematic liquid crystal.Glass substrate with common electrode film (ITO) with horizontal ridges to line up with the horizontal filter.Polarizing filter film with a horizontal axis to block/pass light.Reflective surface to send light back to viewer. (In a backlit LCD, this layer is replaced with a light source.)

Twisted Nematic Devices

The twisted nematic device is the most common LCD application. When no electric field is being applied, the surface alignment directions at the electrodes are perpendicular to each other. The molecules arrange themselves in a helical structure (twisted structure). Some light is able to pass through and some is not, so the result is that the screen appears gray. When the electric field is applied, the crystals in the center layer untwist, and the light is completely blocked from passing through and those pixels will appear black.

Using Interference to Read CDs and DVDs

Optical discs are digital storing media read in an optical disc drive using laser beam.

learning objectives

- Explain how information is stored on the optical disks

Overview

Compact disks (CDs) and digital video disks (DVDs) are examples of optical discs. They are read in an optical disc drive which directs a laser beam at the disc. The reader then detects whether the beam has been reflected or scattered.

Function of Digital Discs

Optical discs are digital storing media. They can store music, files, movies, pictures etc.. These discs are flat, usually made of aluminum, and have microscopic pits and lands on one of the flat surfaces (as shown in). The information on these discs are read by a computer in the form of binary data. First, a laser beam is shot at the disc. If the beam hits a land, it gets reflected back and is recorded as a value of 1. If the beam hits a pit, it gets scattered and is recorded as a value of zero.

Early Version of an Optical Disc: In this early version of an optical disc, you can see the pits and lands which either reflect back light or scatter it.

These microscopic pits and lands cover the entire surface of the disc in a spiral path, starting in the center and working its way outward. The data is stored either by a stamping machine or laser and is read when the data is illuminated by a laser diode in the disc drive. The disc spins at a faster speed when it is being read in the center track, and slower for an outer track. This is because the center tracks are smaller in circumference and therefore can be read quicker.

These pits also act as slits and cause the light to be diffracted as it is reflected back, which causes an iridescent effect. This explains the rainbow pattern that you see on the back of a CD, as shown in.

Compact Disc: The bottom surface of a compact disc showing characteristic iridescence.

Key Points

- In optical microscopy, light reflected from an object passes through the microscope's lenses; this magnifies the light. The resultant, magnified image is then seen by the eye. This technique has many limitations but can be enhanced in various ways to create more contrast.
- The transmission electron microscope (TEM) sends an electron beam through a thin slice of a specimen. The electron is then transmitted onto photographic paper or a screen. Since electron beams have a much smaller wavelength than traditional light, the resolution of this image is much higher.
- The scanning electron microscope (SEM) shows details on the surface of a specimen and produces a three-dimensional view by scanning the specimen.
- The source is placed in front of a mirror, which reflects the light emitted from that object onto a diffraction grating. This grating then disperses the emitted light to anther mirror which spreads the different resultant wavelengths and reflects them onto a detector which records the findings.
- Early forms of spectrometers were simple prisms, but modern spectrometers are automated by a computer and can record a much broader range of frequencies.
- Spectrometers are used in spectroscopy. Spectroscopy studies the interaction between matter and radiated energy. This radiated energy is a function of wavelength and frequency. Every type of atom has its own frequency.
- Interferometry refers to techniques that use superimposed waves to extract information about the waves.
- Michelson interferometer works by splitting a beam of light into two paths, bouncing them back and recombining them to create an interference pattern. To create interference fringes on a detector, the paths may be different lengths or composed of different materials.
- The best known application of the Michelson interferometer is the Michelson-Morley experiment, the unexpected null result of which was an inspiration for special relativity.
- LCDs use an electric field to arrange the liquid crystals into the desired pattern, and then pass light through these layers to produce an image on the screen.
- LCDs can be used to display an arbitrary image made up of tiny fixed pixels, or can be used to display a fixed image, as in on a digital clock.
- A twisted nematic display is the most common LCD in use. This type of display is on calculators, digital watches, and clocks. When no electric field is applied, the molecules are twisted, and let some light through. When the field is applied, they untwist, blocking the light and are seen as black.

- The iridescent layer of the disc is imprinted with tiny pits and lands. Pits scatter light when illuminated, and produce a reading of 0; lands reflect light back and produce a reading of 1.
- The optical disc drive records the 0 and 1 readings and translates them into binary data which is used to relay whatever information is recorded on the disc.
- Rainbow pattern on the back of a CD is due diffraction of the reflected light by pits.

Key Terms

- **microscopy**: using microscopes to view objects that cannot be seen with the naked eye
- **contrast**: A difference in lightness, brightness and/or hue between two colors that makes them more or less distinguishable
- **incandescence**: Incandescence is the emission of light (visible electromagnetic radiation) from a hot body as a result of its temperature.
- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **superimposed**: Positioned on or above something else, especially in layers
- **interference**: An effect caused by the superposition of two systems of waves, such as a distortion on a broadcast signal due to atmospheric or other effects.
- **LCD**: a liquid crystal display.
- **helical**: In the shape of a helix, twist.
- **nematic**: Describing the structure of some liquid crystals whose molecules align in loose parallel lines.
- **binary data**: Data which can take on only two possible values, traditionally termed 0 and 1.
- **pit**: An imprint on an optical disc that scatters light when illuminated.
- **land**: A flat area on an optical disc that reflects light when illuminated.

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CHAPTER OVERVIEW

7: Special Relativity

7.1: Introduction

learning objectives

- Explain why the Galilean invariance didn't work in Maxwell's equations

Galilean invariance or Galilean relativity states that the laws of motion are the same in all inertial (or non-accelerating) frames. Galileo Galilei first described this principle in 1632 using the example of a ship travelling at constant velocity, without rocking, on a smooth sea; any observer doing experiments below the deck would not be able to tell whether the ship was moving or stationary. The fact that the Earth orbits around the sun at approximately 30 km/s offers a somewhat more dramatic example, though it is technically not an inertial reference frame.

Specifically, the term Galilean invariance today usually refers to this principle as applied to Newtonian mechanics—that is, Newton's laws hold in all inertial frames. In this context it is sometimes called Newtonian relativity. Among the axioms from Newton's theory are:

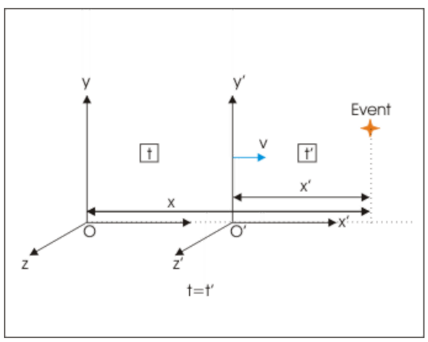
- There exists an absolute space in which Newton's laws are true. An inertial frame is a reference frame in relative uniform motion to absolute space.
- All inertial frames share a universal (or absolute) time.

Derivation

Galilean relativity can be shown as follows. Consider two inertial frames S and S'. A physical event in S will have position coordinates $r = (x, y, z)$ and time t; similarly for S'. By the second axiom above, one can synchronize the clock in the two frames and assume $t = t$'. Suppose S' is in relative uniform motion to S with velocity v. Consider a point object whose position is given by $r = r(t)$ in S. We see that

$$\mathrm{r}'(\mathrm{t}) = \mathrm{r}(\mathrm{t}) - \mathrm{vt} \tag{7.1.1}$$

This transformation of variables between two inertial frames is called Galilean transformation. Now, the velocity of the particle is given by the time derivative of the position:



Galilean Invariance: Newtonian mechanics is invariant under a Galilean transformation between observation frames (shown). This is called Galilean invariance.

$$\mathrm{u}'(\mathrm{t}) = \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{r}'(\mathrm{t}) = \frac{\mathrm{d}}{\mathrm{d}t}\mathrm{r}(\mathrm{t}) - \mathrm{v} = \mathrm{u}(\mathrm{t}) - \mathrm{v} \tag{7.1.2}$$

Another differentiation gives the acceleration in the two frames:

$$\mathrm{a}'(\mathrm{t}) = \frac{\mathrm{d}}{\mathrm{dt}}\mathrm{u}'(\mathrm{t}) = \frac{\mathrm{d}}{\mathrm{dt}}\mathrm{u}(\mathrm{t}) - 0 = \mathrm{a}(\mathrm{t}) \tag{7.1.3}$$

It is this simple but crucial result that implies Galilean relativity. Assuming that mass is invariant in all inertial frames, the above equation shows that Newton's laws of mechanics, if valid in one frame, must hold for all frames. But it is assumed to hold in absolute space, therefore Galilean relativity holds.

Issues

Both Newtonian mechanics and the Maxwell's equations were well established by the end of the 19th century. The puzzle lied in the fact that the Galilean invariance didn't work in Maxwell's equations. That is, unlike Newtonian mechanics, Maxwell's equations are not invariant under a Galilean transformation. Albert Einstein's central insight in formulating special relativity was that, for full consistency with electromagnetism, mechanics must also be revised, such that Lorentz invariance (introduced later) replaces Galilean invariance. At the low relative velocities characteristic of everyday life, Lorentz invariance and Galilean invariance are nearly the same, but for relative velocities close to that of light they are very different.

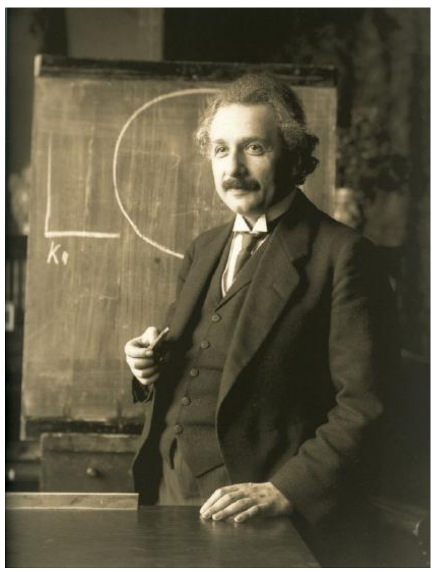
Einstein's Postulates

Special relativity is based on Einstein's two postulates: the Principle of Relativity and the Principle of Invariant Light Speed.

learning objectives

- Identify two postulates forming the foundation of special relativity

In the late 19th century, the Newtonian mechanics was considered to be valid in all inertial frames of reference, which are moving at a constant relative velocity with respect to each other. (See our previous lesson on "Galilean-Newtonian Relativity. ") One issue, however, was that another well-established theory, the laws of electricity and magnetism represented by Maxwell's equations, was not "invariant" under Galilean transformation—meaning that Maxwell's equations don't maintain the same forms for different inertial frames. In his "Special Theory of Relativity," Einstein resolved the puzzle and broadened the scope of the invariance to extend the validity of all physical laws, including electromagnetic theory, to all inertial frames of reference.



Albert Einstein: Albert Einstein, a true pioneer of modern physics. His work on relativity, gavity, quantum mechanics, and statistical physics revolutionized physics.

Einstein's Postulates

With two deceptively simple postulates and a careful consideration of how measurements are made, Einstein produced the theory of special relativity.

1. The Principle of Relativity: The laws of physics are the same and can be stated in their simplest form in all inertial frames of reference.

This postulate relates to reference frames. It says that there is no preferred frame and, therefore, no absolute motion.

2. The Principle of Invariant Light Speed: The speed of light c is a constant, independent of the relative motion of the source and observer.

The laws of electricity and magnetism predict that light travels at $c = 2.998 \times 10^8$ m/s in a vacuum, but they do not specify the frame of reference in which light has this speed. Physicists assumed that there exists a stationary medium for the propagation of light, which they called " luminiferous aether. " In 1887, Michelson and Morley attempted to detect the relative motion of the Earth through the stationary luminiferous aether, but their negative results implied the speed of light c is independent of the motion of the source relative to the observer. Einstein accepted the result of the experiment and incorporated it in his theory of relativity.

This postulate might sound easy to accept, but it is rather counterintuitive. Imagine that you can throw a baseball at a speed v (relative to you). If you are on a train moving at a speed V and throw a ball in the direction of the train's movement, the baseball will travel at a speed $v+V$ for an observer stationary on the ground.

Now, instead of a baseball, let's say you have a laser pointer. You turn on the laser pointer while you are on a moving train. What would be the speed of light from the laser pointer for a stationary observer on the ground? Our intuition says that it should be $c+V$. However, Einstein says that it should be only c!

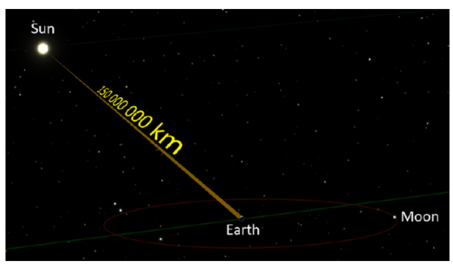
The Speed of Light

The speed of light in vacuum is a universal physical constant crucial to many areas of physics.

learning objectives

- Discuss the invariance of the speed of light and identify the value of that speed in vacuum

The speed of light in vacuum, commonly denoted c, is a universal physical constant that is crucial to many areas of physics. Its value is 299,792,458 m/s; this is a precise known value because the length of the meter is itself derived from this constant and the international standard for time. According to special relativity, c is the maximum speed at which all energy, matter, and information in the universe can travel. It is the speed at which all massless particles and associated fields (including electromagnetic radiation such as light) travel in vacuum. It is also the speed of gravity (i.e., of gravitational waves) predicted by current theories. Such particles and waves (including light) travel at c regardless of the motion of the source or the inertial frame of reference of the observer. In the theory of relativity, c interrelates space and time in the Lorentz transformation; it also appears in the famous equation of mass-energy equivalence: $E = mc^2$.



Sunlight's Flight to Earth: Sunlight takes about 8 minutes and 19 seconds to reach the earth (based on the average distance between the sun and the earth)

First Measurement

The first quantitative estimate of the speed of light was made in 1676 by Rømer. From the observation that the periods of Jupiter's innermost moon (Io) appeared to be shorter when Earth was approaching Jupiter than when it was moving away, he concluded that light travels at a finite speed. He estimated that it takes light 22 minutes to cross the diameter of Earth's orbit. Christiaan Huygens combined this estimate with an estimate for the diameter of the Earth's orbit to obtain an estimate of the speed of light of 220,000 km/s, 26 percent lower than the actual value.

Fundamental Role in Physics

The speed at which light waves propagate in vacuum is independent both of the motion of the wave source and of the inertial frame of reference of the observer. This invariance of the speed of light was postulated by Einstein in 1905 after being motivated by Maxwell's theory of electromagnetism and the lack of evidence for "luminiferous aether"; it has since been consistently confirmed by many experiments.

Key Points

- Galilean invariance states that Newton's laws hold in all inertial frames.
- Newtonian mechanics assumes that there exists an absolute space and that time is universal.

- Albert Einstein’s central insight in formulating special relativity was that, for full consistency with electromagnetism, mechanics must also be revised such that Lorentz invariance (introduced later) replaces Galilean invariance.
- The special theory of relativity explores the consequences of the invariance of *c* with the assumption that the laws of physics are the same in all inertial frames of reference.
- Einstein’s first postulate says that the laws of physics are the same and can be stated in their simplest form in all inertial frames of reference. It means that there is no preferred frame and, therefore, no absolute motion.
- The speed of light *c* is a constant, independent of the relative motion of the source and observer.
- The speed at which light waves propagate in vacuum is independent both of the motion of the wave source and of the inertial frame of reference of the observer. This invariance of the speed of light was postulated by Einstein in 1905 in his work on special relativity.
- The value of the speed of light is 299,792,458 m/s; this is a precise known value because the length of the meter is itself derived from this constant and the international standard for time.
- *c* is the maximum speed at which all energy, matter, and information in the universe can travel.

Key Terms

- **Lorentz invariance**: First introduced by Lorentz in an effort to explain how the speed of light was observed to be independent of the reference frame, and to understand the symmetries of the laws of electromagnetism.
- **absolute space**: A concept introduced by Newton that assumes space remains always similar and immovable.
- **Maxwell’s equations**: A set of equations describing how electric and magnetic fields are generated and altered by each other and by charges and currents.
- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **luminiferous aether**: Light-bearing aether; the postulated medium for the propagation of light.
- **Lorentz transformation**: a transformation relating the spacetime coordinates of one frame of reference to another in special relativity

7.2: Consequences of Special Relativity

learning objectives

- Formulate conclusions of the theory of special relativity, noting the assumptions that were made in deriving it

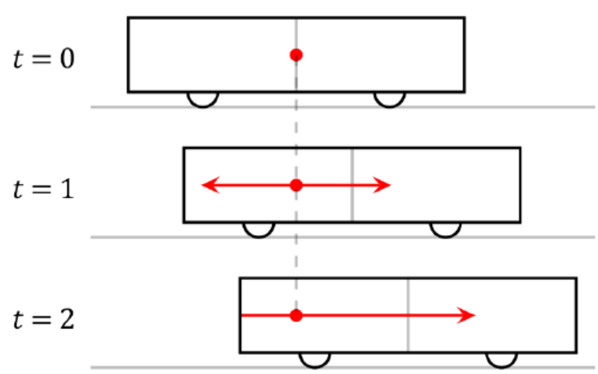
The relativity of simultaneity is the concept that simultaneity–whether two events occur at the same time–is not absolute, but depends on the observer's frame of reference.

According to the theory of special relativity, it is impossible to say in an absolute sense whether two distinct events occur at the same time if those events are separated in space, such as a car crash in London and another in New York. The question of whether the events are simultaneous is relative: in some reference frames the two accidents may happen at the same time, in other frames (in a different state of motion relative to the events) the crash in London may occur first, and still in other frames, the New York crash may occur first. If the two events are causally connected ("event A causes event B"), then the relativity of simultaneity preserves the causal order (i.e. "event A causes event B" in all frames of reference).

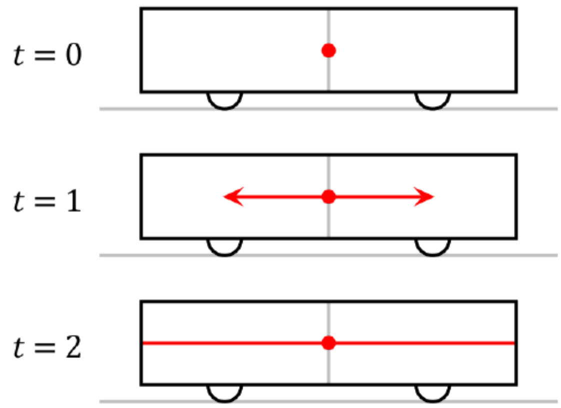
If we imagine one reference frame assigns precisely the same time to two events that are at different points in space, a reference frame that is moving relative to the first will generally assign different times to the two events. This is illustrated in the ladder paradox, a thought experiment which uses the example of a ladder moving at high speed through a garage.

A mathematical form of the relativity of simultaneity ("local time") was introduced by Hendrik Lorentz in 1892, and physically interpreted (to first order in v/c) as the result of a synchronization using light signals by Henri Poincaré in 1900. However, both Lorentz and Poincaré based their conceptions on the aether as a preferred but undetectable frame of reference, and continued to distinguish between "true time" (in the aether) and "apparent" times for moving observers.

In 1905, Albert Einstein abandoned the (classical) aether and emphasized the significance of relativity of simultaneity to our understanding of space and time. He deduced the failure of absolute simultaneity from two stated assumptions: 1) the principle of relativity–the equivalence of inertial frames, such that the laws of physics apply equally in all inertial coordinate systems; 2) the constancy of the speed of light detected in empty space, independent of the relative motion of its source.



Observer Standing on the Platform: Reference frame of an observer standing on the platform (length contraction not depicted).



Observer Onboard the Train: The train-and-platform experiment from the reference frame of an observer onboard the train.

Time Dilation

Time dilation is an actual difference of elapsed time between two events as measured by observers moving relative to each other.

learning objectives

- Explain why time dilation can be ignored in daily life

Time dilation is an actual difference of elapsed time between two events as measured by observers either moving relative to each other.

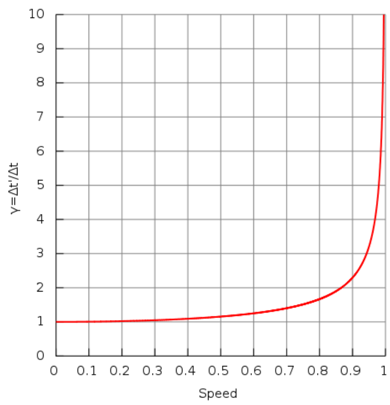
For instance, two rocket ships (A and B) speeding past one another in space would experience time dilation. If they somehow had a clear view into each other's ships, each crew would see the others' clocks and movement as going too slowly. That is, inside the frame of reference of Ship A, everything is moving normally, but everything over on Ship B appears to be moving slower (and vice versa).

From a local perspective, time registered by clocks that are at rest with respect to the local frame of reference (and far from any gravitational mass) always appears to pass at the same rate. In other words, if a new ship, Ship C, travels alongside Ship A, it is "at rest" relative to Ship A. From the point of view of Ship A, new Ship C's time would appear normal too.

The formula for determining time dilation is: $\Delta t' = \gamma \Delta t = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$

where Δt is the time interval between two co-local events (i.e. happening at the same place) for an observer in some inertial frame (e.g. ticks on his clock), this is known as the proper time, $\Delta t'$ is the time interval between those same events, as measured by another observer, inertially moving with velocity v with respect to the former observer, v is the relative velocity between the observer and the moving clock, c is the speed of light, and $\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$

is the Lorentz factor. Thus the duration of the clock cycle of a moving clock is found to be increased: it is measured to be "running slow". Note that for speeds below 1/10 the speed of light, Lorentz factor is approximately 1. Thus, time dilation effects and extremely small and can be safely ignored in a daily life. They become important only when an object approaches speeds on the order of 30,000 km/s (1/10 the speed of light).



Lorentz Factor: Lorentz factor as a function of speed (in natural units where c = 1). Notice that for small speeds (less than 0.1), γ is approximately 1.

Effects of Time Dilation: The Twin Paradox and the Decay of the Muon

The twin paradox is a thought experiment: one twin makes a journey into space and returns home to find that twin remained aged more.

learning objectives

- Explain the twin paradox within the standard framework of special relativity

The twin paradox is a thought experiment in special relativity involving identical twins, one of whom makes a journey into space in a high-speed rocket and returns home to find that the twin who remained on Earth has aged more.

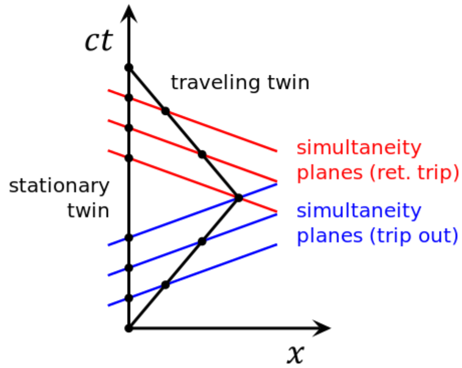
This occurs because special relativity shows that the faster one travels, the slower time moves for them.

This result appears puzzling because each twin sees the other twin as traveling, and so, according to a naive application of time dilation, each should paradoxically find the other to have aged more slowly. In other words, from the perspective of the rocketship, the earth is traveling away from the ship and from the perspective of the earth, the rocket is traveling away.

However, this scenario can be resolved within the standard framework of special relativity (because the twins are not equivalent; the space twin experienced additional, asymmetrical acceleration when switching direction to return home), and therefore is not a paradox in the sense of a logical contradiction.

The Earth and the ship are not in a symmetrical relationship: regardless of whether we view the situation from the perspective of the Earth or the ship, the ship experiences additional acceleration forces. The ship has a turnaround in which it accelerates and changes direction whereas the earth does not. Since there is no symmetry, it is not paradoxical if one twin is younger than the other. Nevertheless twin paradox is useful as a demonstration that special relativity is self-consistent.

In the spacetime diagram, drawn for the reference frame of the Earth-based twin, that twin's world line coincides with the vertical axis (his position is constant in space, moving only in time). On the first leg of the trip, the second twin moves to the right (black sloped line); and on the second leg, back to the left. Blue lines show the planes of simultaneity for the traveling twin during the first leg of the journey; red lines, during the second leg. Just before turnaround, the traveling twin calculates the age of the Earth-based twin by measuring the interval along the vertical axis from the origin to the upper blue line. Just after turnaround, if he recalculates, he'll measure the interval from the origin to the lower red line. In a sense, during the U-turn the plane of simultaneity jumps from blue to red and very quickly sweeps over a large segment of the world line of the Earth-based twin. The traveling twin reckons that there has been a jump discontinuity in the age of the Earth-based twin.



Spacetime Diagram of the Twin Paradox: Spacetime diagram of the twin paradox. Time is relative, but both twins are not equivalent (the ship experiences additional acceleration to changes the direction of travel).

Length Contraction

Objects that are moving undergo a length contraction along the dimension of motion; this effect is only significant at relativistic speeds.

learning objectives

- Explain why length contraction can be ignored in daily life

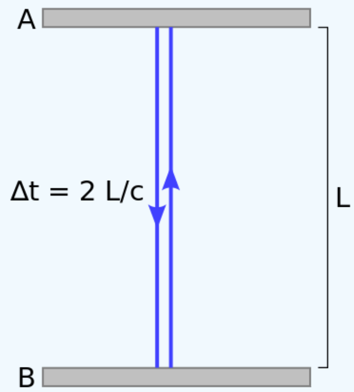
Length contraction is the physical phenomenon of a decrease in length detected by an observer of objects that travel at any non-zero velocity relative to that observer. Length contraction arises due to the fact that the speed of light in a vacuum is constant in any frame of reference. By taking this into account, as well as some geometrical considerations, we will show how perceived time and length are affected.

Example 7.2.1:

Let us imagine a simple clock system that consists of two mirrors A and B in a vacuum. A light pulse bounces between the two mirrors. The separation of the mirrors is L, and the clock ticks once each time the light pulse hits a given mirror. Now imagine that the clock is at rest. The time that it will take for the light pulse to go from mirror A to mirror B and then back to mirror A be can be described by:

$$\Delta t=\frac{2\mathrm{L}}{c} \tag{7.2.1}$$

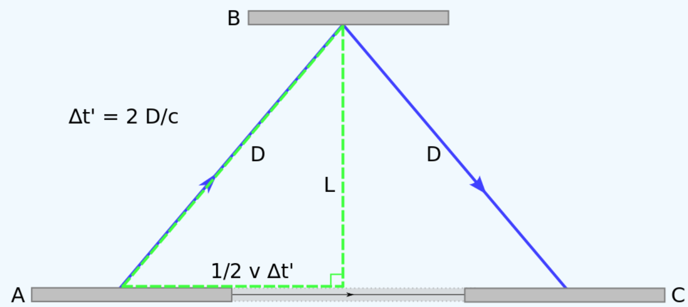
where c is the speed of light. Now imagine that the clock is moving in the horizontal direction relative to a stationary observer. The light pulse is emitted from mirror A. To the stationary observer, it appears that the light pulse has a longer path to travel because by the time the light reaches mirror B the clock has already moved somewhat in the horizontal direction. This is the same case for the light pulse on its way back. The stationary observer will perceive that it will take the light a total of:



Geometry for a Clock at Rest: This illustrates the path that light must traverse when the clock is at rest.

$$\Delta t' = \frac{2D}{c} \tag{7.2.2}$$

to traverse its path. We can see that D is longer than L, so that means that.

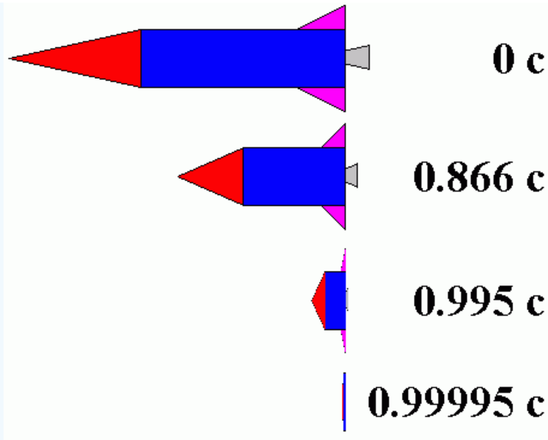


Geometry for a Moving Clock: This illustrates the path that light must traverse when the clock is moving from the perspective of a stationary observer.

Example 7.2.2:

We have established that in a frame of reference that is moving relative to the clock (the stationary observer is moving in the clock's frame of reference), the clock appears to run more slowly. Now let us imagine that we want to measure the length of a ruler. This time let us imagine that you are moving with velocity *v*. You can mathematically determine the length of the ruler in your frame of reference (*L*‘) by multiplying your velocity (*v*) by the time that you perceive that it takes you to pass by the ruler (*t*‘). Expressing this in equation form, *L*‘ = *vt*‘. Now, if someone in the ruler's rest frame wanted to determine the length of the ruler, they could do the following. They could mathematically determine the length of the ruler in their frame of reference (*L*) by multiplying your velocity (*v*) by the time that they perceive that it takes you to pass by the ruler (*t*). This is expressed in the following equation: *L* = *vt*. Just as in the clock explanation, the ruler appears to be moving in your frame of reference, so *t* will be longer than *t*‘ (your time interval). Consequently, the length of the ruler will appear to be shorter in your frame of reference (the phenomenon of length contraction occurred).

The effect of length contraction is negligible at everyday speeds and can be ignored for all regular purposes. Length contraction becomes noticeable at a substantial fraction of the speed of light (as illustrated in) with the contraction only in the direction parallel to the direction in which the observed body is travelling.



Observed Length of an Object: Observed length of an object at rest and at different speeds

Example 7.2.3:

For example, at a speed of 13,400,000 m/s (30 million mph,.0447*c*), the length is 99.9 percent of the length at rest; at a speed of 42,300,000 m/s (95 million mph, 0.141*c*), the length is still 99 percent. As the magnitude of the velocity approaches the speed of light, the effect becomes dominant.The mathematical formula for length contraction is:

$$\mathrm{L}=\frac{\mathrm{L}_0}{\gamma(v)}=\mathrm{L}_0\sqrt{1-\frac{v^2}{\mathrm{c}^2}} \tag{7.2.3}$$

where L_0 is the proper length (the length of the object in its rest frame); L is the length observed by an observer in relative motion with respect to the object; v is the relative velocity between the observer and the moving object; c is the speed of light; and the Lorentz factor is defined as:

$$\gamma(v)=\frac{1}{\sqrt{1-v^2/c^2}} \tag{7.2.4}$$

In this equation it is assumed that the object is parallel with its line of movement. For the observer in relative movement, the length of the object is measured by subtracting the simultaneously measured distances of both ends of the object. An observer at rest viewing an object traveling very close to the speed of light would observe the length of the object in the direction of motion as very close to zero.

Key Points

- According to the theory of special relativity, it is impossible to say in an absolute sense whether two distinct events occur at the same time if those events are separated in space.
- A mathematical form of the relativity of simultaneity was introduced by Hendrik Lorentz and physically interpreted by Henri Poincaré. The conceptions were based on the aether as a preferred but undetectable frame of reference.
- Albert Einstein deduced the failure of absolute simultaneity from two assumptions: 1) the principle of relativity; 2) the constancy of the speed of light detected in empty space, independent of the relative motion of its source.
- Time dilation effects are extremely small for speeds below 1/10 the speed of light and can be safely ignored at daily life.
- Time dilation effects become important when an object approaches speeds on the order of 30,000 km/s (1/10 the speed of light).
- The formula for determining time dilation is: $\Delta\mathrm{t}'=\frac{\Delta\mathrm{t}}{\sqrt{1-\mathrm{v}^2/\mathrm{c}^2}}$.
- From a naive application of time dilation, each twin should paradoxically find the other to have aged more slowly.
- The scenario is resolved within the standard framework of special relativity: the twins are not equivalent, the space twin experiences additional, asymmetrical acceleration when switching direction to return home.
- Twin paradox is useful as a demonstration that special relativity is self-consistent.
- Length contraction is negligible at everyday speeds and can be ignored for all regular purposes.

- Length contraction becomes noticeable at a substantial fraction of the speed of light with the contraction only in the direction parallel to the direction in which the observed body is travelling.
- An observer at rest viewing an object travelling very close to the speed of light would observe the length of the object in the direction of motion as very near zero.

Key Terms

- **aether**: A space-filling substance or field, thought to be necessary as a transmission medium for the propagation of electromagnetic or gravitational forces.
- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **speed of light**: the speed of electromagnetic radiation in a perfect vacuum: exactly 299,792,458 meters per second by definition
- **time dilation**: The slowing of the passage of time experienced by objects in motion relative to an observer; measurable only at relativistic speeds.
- **Lorentz factor**: The factor, used in special relativity, to calculate the degree of time dilation, length contraction and relativistic mass of an object moving relative to an observer.

7.3: Relativistic Quantities

learning objectives

- Express velocity-addition formulas for objects at speeds much less and approaching the speed of light

A velocity-addition formula is an equation that relates the velocities of moving objects in different reference frames.

As Galileo Galilei observed in 17th century, if a ship is moving relative to the shore at velocity vv, and a fly is moving with velocity uu as measured on the ship, calculating the velocity of the fly as measured on the shore is what is meant by the addition of the velocities vv and uu. When both the fly and the ship are moving slowly compared to speed of light, it is accurate enough to use the vector sum s=u+vs=u+v where ss is the velocity of the fly relative to the shore.

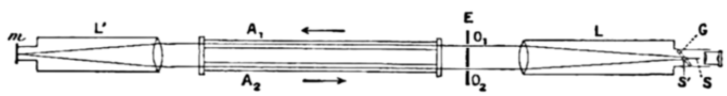
According to the theory of special relativity, the frame of the ship has a different clock rate and distance measure, and the notion of simultaneity in the direction of motion is altered, so the addition law for velocities is changed.

Since special relativity dictates that the speed of light is the same in all frames of reference, light shone from the front of a moving car can't go faster than light from a stationary lamp. Since this is counter to what Galileo used to add velocities, there needs to be a new velocity addition law.

This change isn't noticeable at low velocities but as the velocity increases towards the speed of light it becomes important. The addition law is also called a composition law for velocities. For collinear motions, the velocity of the fly relative to the shore is given by the following equation:

$$\mathrm{s} = \frac{\mathrm{v}+\mathrm{u}}{1+\mathrm{vu}/\mathrm{c}^2} \tag{7.3.1}$$

Composition law for velocities gave the first test of the kinematics of the special theory of relativity. Using a Michelson interferometer, Hyppolite Fizeau measured the speed of light in a fluid moving parallel to the light in 1851. The speed of light in the fluid is slower than the speed of light in vacuum, and it changes if the fluid is moving along with the light. The speed of light in a collinear moving fluid is predicted accurately by the collinear case of the relativistic formula.



Setup of the Fizeau Experiment: A light ray emanating from the source S' is reflected by a beam splitter G and is collimated into a parallel beam by lens L. After passing the slits O1 and O2, two rays of light travel through the tubes A1 and A2, through which water is streaming back and forth as shown by the arrows. The rays reflect off a mirror m at the focus of lens L', so that one ray always propagates in the same direction as the water stream, and the other ray opposite to the direction of the water stream. After passing back and forth through the tubes, both rays unite at S, where they produce interference fringes that can be visualized through the illustrated eyepiece. The interference pattern can be analyzed to determine the speed of light traveling along each leg of the tube.

Relativistic Momentum

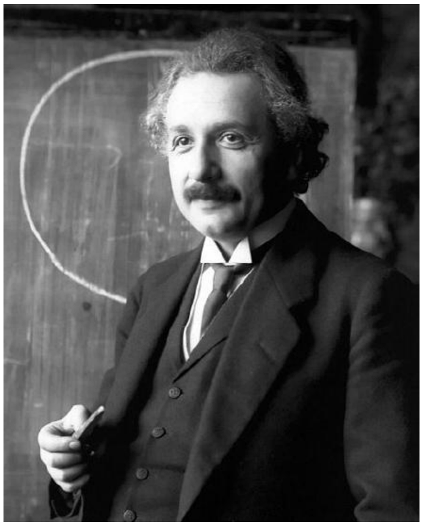
Relativistic momentum is given as $\gamma \mathrm{m}_0 \mathrm{v}$ where m_0 is the object's invariant mass and γ is Lorentz transformation.

learning objectives

- Compare Newtonian and relativistic momenta for objects at speeds much less and approaching the speed of light

Relativistic Momentum

Newtonian physics assumes that absolute time and space exist outside of any observer. This gives rise to Galilean relativity, which states that the laws of motion are the same in all inertial frames. It also results in a prediction that the speed of light can vary from one reference frame to another. However, this is contrary to observation. In the theory of special relativity, Albert Einstein keeps the postulate that the equations of motion do not depend on the reference frame, but assumes that the speed of light *c* is invariant. As a result, position and time in two reference frames are related by the Lorentz transformation instead of the Galilean transformation.



Albert Einstein: Albert Einstein in 1921

Consider, for example, a reference frame moving relative to another at velocity *v* in the *x* direction. The Galilean transformation gives the coordinates of the moving frame as

$$t' = t \tag{7.3.2}$$

$$x' = x - vt \tag{7.3.3}$$

while the Lorentz transformation gives

$$t' = \gamma \left(t - \frac{vx}{c^2}\right) \tag{7.3.4}$$

$$x' = \gamma(x - vt) \tag{7.3.5}$$

where γ is the Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \tag{7.3.6}$$

Conservation laws in physics, such as the law of conservation of momentum, must be invariant. That is, the property that needs to be conserved should remain unchanged regardless of changes in the conditions of measurement. This means that the conservation law needs to hold in any frame of reference. Newton's second law [with mass fixed in the expression for momentum (p=m*v)], is not invariant under a Lorentz transformation. However, it can be made invariant by making the inertial mass *m* of an object a function of velocity:

$$m = \gamma m_0 \tag{7.3.7}$$

where m_0 is the object's invariant mass.

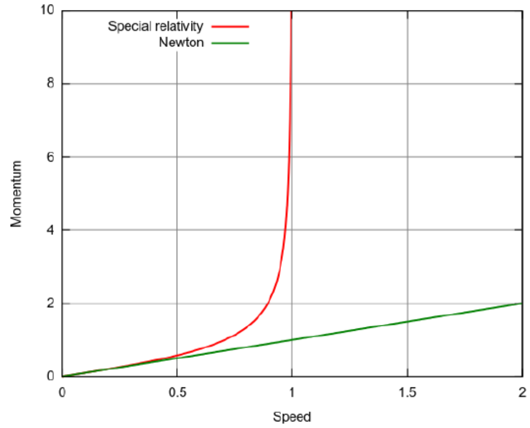
The modified momentum,

$$p = \gamma m_0 v \tag{7.3.8}$$

obeys Newton's second law:

$$F = \frac{dp}{dt} \tag{7.3.9}$$

It is important to note that for speeds much less than the speed of light, Newtonian momentum and relativistic momentum are approximately the same. As one approaches the speed of light, however, relativistic momentum becomes infinite while Newtonian momentum continues to increases linearly. Thus, it is necessary to employ the expression for relativistic momentum when one is dealing with speeds near the speed of light.



Relativistic and Newtonian Momentum: This figure illustrates that relativistic momentum approaches infinity as the speed of light is approached. Newtonian momentum increases linearly with speed.

Relativistic Energy and Mass

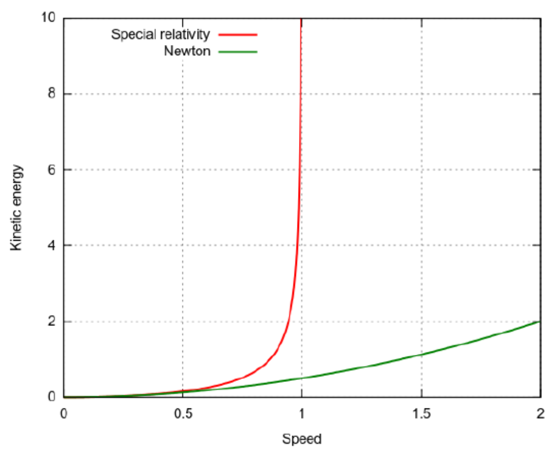
In special relativity, as the object approaches the speed of light, the object's energy and momentum increase without bound.

learning objectives

- Evaluate possibility for an object to travel at the speed of light

Relativistic Energy and Mass

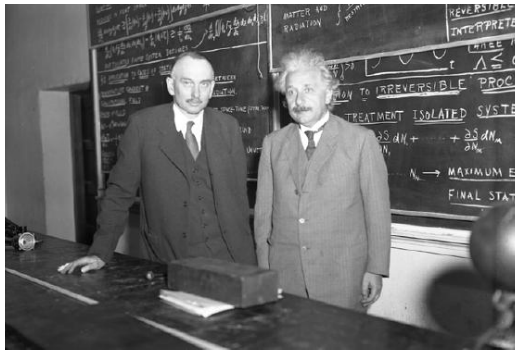
In special relativity, an object that has a mass cannot travel at the speed of light. As the object approaches the speed of light, the object's energy and momentum increase without bound. Relativistic corrections for energy and mass need to be made because of the fact that the speed of light in a vacuum is constant in all reference frames. The conservation of mass and energy are well-accepted laws of physics. In order for these laws to hold in all reference frames, special relativity must be applied. It is important to note that for objects with speeds that are well below the speed of light that the expressions for relativistic energy and mass yield values that are approximately equal to their Newtonian counterparts.



Relativistic and Newtonian Kinetic Energy: This figure illustrates how relativistic and Newtonian Kinetic Energy are related to the speed of an object. The relativistic kinetic energy increases to infinity when an object approaches the speed of light, this indicates that no body with mass can reach the speed of light. On the other hand, Newtonian kinetic energy continues to increase without bound as the speed of an object increases.

Relativistic Mass

Relativistic mass was defined by Richard C. Tolman pictured left of Albert Einstein here in 1934 as $m = E/c^2$ which holds for all particles, including those moving at the speed of light. For a slower than light particle, a particle with a nonzero rest mass, the formula becomes $m = m_o/\gamma$ where m_o is the rest mass and γ is the Lorentz factor. The Lorentz factor is equal to: $\gamma = \frac{1}{\sqrt{1 - \mathrm{v}^2/c^2}}$, where v is the relative velocity between inertial reference frames and c is the speed of light.



Richard C. Tolman and Albert Einstein: Richard C. Tolman (1881 – 1948) with Albert Einstein (1879 – 1955) at Caltech, 1932

When the relative velocity is zero, γ is simply equal to 1, and the relativistic mass is reduced to the rest mass. As the velocity increases toward the speed of light (c), the denominator of the right side approaches zero, and m consequently approaches infinity.

In the formula for momentum the mass that occurs is the relativistic mass. In other words, the relativistic mass is the proportionality constant between the velocity and the momentum.

While Newton's second law remains valid in the form $\mathbf{f} = \frac{d\mathbf{p}}{dt}$ the derived form is not valid because m in $\mathbf{p}$ is generally not a constant.

Relativistic Energy

Relativistic energy ($\mathrm{E_r} = \sqrt{(\mathrm{m_0 c^2})^2 + (\mathrm{pc})^2}$) is connected with rest mass via the following equation: $\mathrm{m_0} = \frac{\sqrt{(E^2 - (pc)^2}}{c^2}$. Here the term represents the square of the Euclidean norm (total vector length) of the various momentum vectors in the system, which reduces to the square of the simple momentum magnitude, if only a single particle is considered. This equation reduces to when the momentum term is zero. For photons where the equation reduces to.

Today, the predictions of relativistic energy and mass are routinely confirmed from the experimental data of particle accelerators such as the Relativistic Heavy Ion Collider. The increase of relativistic momentum and energy is not only precisely measured but also necessary to understand the behavior of cyclotrons and synchrotron, which accelerate particles to near the speed of light.

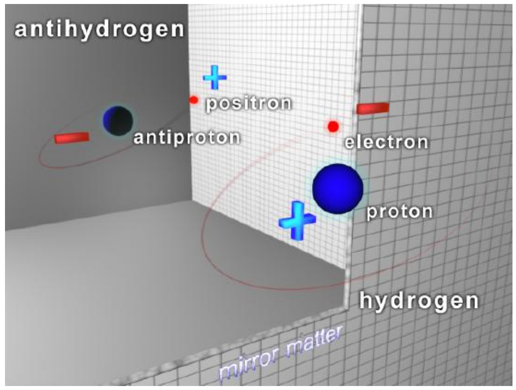
Matter and Antimatter

Antimatter is composed of antiparticles, which have the same mass as particles of ordinary matter but opposite charge and quantum spin.

learning objectives

- Describe properties of antiparticles

Antimatter is material composed of antiparticles, which have the same mass as particles of ordinary matter but have opposite charge and quantum spin. Antiparticles bind with each other to form antimatter in the same way that normal particles bind to form normal matter. For example, a positron (the antiparticle of the electron, with symbol e^+) and an antiproton (symbol p^-) can form an antihydrogen atom. Furthermore, mixing matter and antimatter can lead to the annihilation of both, in the same way that mixing antiparticles and particles does. This gives rise to high-energy photons (gamma rays) and other particle-antiparticle pairs. The end result of antimatter meeting matter is a release of energy proportional to the mass, as shown in the mass-energy equivalence equation, $E = mc^2$.



Antihydrogen and Hydrogen Atoms: Antihydrogen consists of an antiproton and a positron; hydrogen consists of a proton and an electron.

Almost all matter observable from the earth seems to be made of matter rather than antimatter. If antimatter-dominated regions of space existed, the gamma rays produced in annihilation reactions along the boundary between matter and antimatter regions would be detectable.

Antimatter may still exist in relatively large amounts in far-away galaxies due to cosmic inflation in the primordial time of the universe. Antimatter galaxies, if they exist, are expected to have the same chemistry and absorption and emission spectra as normal-matter galaxies, and their astronomical objects would be observationally identical, making them difficult to distinguish from normal-matter galaxies.

There is considerable speculation as to why the observable universe is apparently composed almost entirely of matter (as opposed to a mixture of matter and antimatter), whether there exist other places that are almost entirely composed of antimatter instead, and what sorts of technology might be possible if antimatter could be harnessed. At this time, the apparent asymmetry of matter and antimatter in the visible universe is one of the greatest unsolved problems in physics.

Relativistic Kinetic Energy

Relativistic kinetic energy can be expressed as: $\mathrm{E_k} = \frac{\mathrm{m_0 c^2}}{\sqrt{1-(\mathrm{v/c})^2)}} - \mathrm{m_0 c^2}$ where m_0 is rest mass, v is velocity, c is speed of light.

learning objectives

- Compare classical and relativistic kinetic energies for objects at speeds much less and approaching the speed of light

In classical mechanics, the kinetic energy of an object depends on the mass of a body as well as its speed. The kinetic energy is equal to the mass multiplied by the square of the speed, multiplied by the constant 1/2. The equation is given as:

$$\mathrm{E_k} = \frac{1}{2}\mathrm{mv^2} \tag{7.3.10}$$

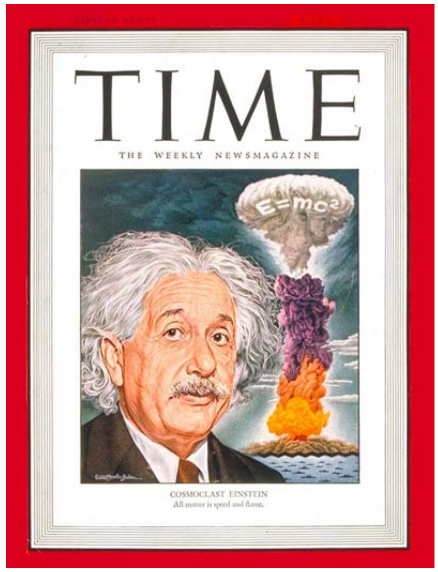
where m is the mass and v is the speed (or the velocity) of the body.

The classical kinetic energy of an object is related to its momentum by the equation:

$$\mathrm{E_k} = \frac{\mathrm{p^2}}{\mathrm{2m}} \tag{7.3.11}$$

where p is momentum.

If the speed of a body is a significant fraction of of the speed of light, it is necessary to employ special relativity to calculate its kinetic energy. It is important to know how to apply special relativity to problems with high speed particles. In special relativity, we must change the expression for linear momentum. Using m for rest mass, v and $\mathcal{V}$ for the object's velocity and speed respectively, and c for the speed of light in vacuum, the relativistic expression for linear momentum is:



Time Magazine – July 1, 1946: The popular connection between Einstein, $E = mc^2$, and the atomic bomb was prominently indicated on the cover of Time magazine (July 1946) by the writing of the equation on the mushroom cloud itself.

$p = m_0 \gamma v$, where γ is the Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

Since the kinetic energy of an object is related to its momentum, we intuitively know that the relativistic expression for kinetic energy will also be different from its classical counterpart. Indeed, the relativistic expression for kinetic energy is:

$$E_k = \frac{m_0 c^2}{\sqrt{1-(v/c)^2)}} - m_0 c^2 \tag{7.3.12}$$

The equation shows that the energy of an object approaches infinity as the velocity v approaches the speed of light c. Thus it is impossible to accelerate an object across this boundary.

The mathematical by-product of this calculation is the mass-energy equivalence formula (referred to in). The body at rest must have energy content equal to:

$$E_{rest} = E_0 = m_0 c^2 \tag{7.3.13}$$

The general expression for the kinetic energy of an object that is not at rest is:

$KE = mc^2 - m_0 c^2$, where m is the relativistic mass of the object and m_0 is the rest mass of the object.

At a low speed (v<<cv<<c), the relativistic kinetic energy may be approximated well by the classical kinetic energy. We can show this to be true by using a Taylor expansion for the reciprocal square root and keeping first two terms of the relativistic kinetic energy equation. When we do this we get:

$$E_k \approx m_0 c^2 \left(1 + \frac{1}{2} v^2/c^2\right) - m_0 c^2 = \frac{1}{2} m v^2 \tag{7.3.14}$$

Thus, the total energy can be partitioned into the energy of the rest mass plus the traditional classical kinetic energy at low speeds.

Key Points

- When two objects are moving slowly compared to speed of light, it is accurate enough to use the vector sum of velocities: $s = u + v$.
- As the velocity increases towards the speed of light, the vector sum of velocities is replaced with: $s = \frac{v+u}{1+vu/c^2}$.
- Composition law for velocities gave the first test of the kinematics of the special theory of relativity when, using a Michelson interferometer, Hyppolite Fizeau measured the speed of light in a fluid moving parallel to the light.

- Newtonian physics assumes that absolute time and space exist outside of any observer, resulting in a prediction that the speed of light can vary from one reference frame to another.
- In the theory of special relativity, the equations of motion do not depend on the reference frame while the speed of light (c) is invariant.
- Within the domain of classical mechanics, relativistic momentum closely approximates Newtonian momentum. At low velocity γm0vγm0v is approximately equal to m0vm0v, the Newtonian expression for momentum.
- In special relativity, an object that has a mass cannot travel at the speed of light.
- Relativistic mass is defined as $m_{rel} = \frac{E}{c^2}$ and can be viewed as the proportionality constant between the velocity and the momentum.
- Relativistic energy is connected with rest mass via the following equation: $E_r = \sqrt{(m_0c^2)^2 + (pc)^2}$.
- The end result of antimatter meeting matter is a release of energy proportional to the mass, as shown in the mass-energy equivalence equation,$E = mc^2$.
- Although almost all matter observable from the Earth seems to be made of matter rather than antimatter, antimatter may still exist in relatively large amounts in far-away galaxies.
- No explanation for the apparent asymmetry of matter and antimatter in the visible universe exists.
- Relativistic kinetic energy equation shows that the energy of an object approaches infinity as the velocity approaches the speed of light. Thus it is impossible to accelerate an object across this boundary.
- Kinetic energy calculations lead to the mass -energy equivalence formula: $E_{rest} = E_0 = mc^2$.
- At a low speed ($v << C$), the relativistic kinetic energy may be approximated by the classical kinetic energy. Thus, the total energy can be partitioned into the energy of the rest mass plus the traditional Newtonian kinetic energy at low speeds.

Key Terms

- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **interferometer**: Any of several instruments that use the interference of waves to determine wavelengths and wave velocities, determine refractive indices, and measure small distances, temperature changes, stresses, and many other useful measurements.
- **speed of light**: the speed of electromagnetic radiation in a perfect vacuum: exactly 299,792,458 meters per second by definition
- **Galilean transformation**: a transformation used to transform between the coordinates of two reference frames which differ only by constant relative motion within the constructs of Newtonian physics.
- **Lorentz transformation**: a transformation relating the spacetime coordinates of one frame of reference to another in special relativity
- **Lorentz factor**: The factor, used in special relativity, to calculate the degree of time dilation, length contraction and relativistic mass of an object moving relative to an observer.
- **rest mass**: the mass of a body when it is not moving relative to an observer
- **annihilation**: the process of a particle and its corresponding antiparticle combining to produce energy
- **positron**: The antimatter equivalent of an electron, having the same mass but a positive charge.
- **antimatter**: matter that is composed of the antiparticles of those that constitute normal matter
- **classical mechanics**: All of the physical laws of nature that account for the behaviour of the normal world, but break down when dealing with the very small (see quantum mechanics) or the very fast or very heavy (see relativity).

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7.4: Implications of Special Relativity

learning objectives

- Formulate major changes in the understanding of time, space, mass, and energy that were introduced by the theory of Special Relativity

The theory of Special Relativity and its implications spurred a paradigm shift in our understanding of the nature of the universe, the fundamental fabric of which being space and time. Before 1905, scientists considered space and time as completely independent objects. Time could not affect space and space could not affect time. After 1905, however, the Special Theory of Relativity destroyed this old, but intuitive, view. Specifically, Special Relativity showed us that space and time are not independent of one another but can be mixed into each other and therefore must be considered as the same object, which we shall denote as space-time. The consequences of space/time mixing are:

- time dilation
- and length contraction.

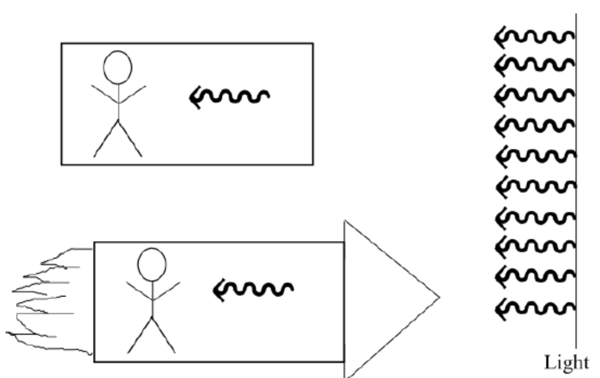
Other important consequences which will be discussed in another section are

- Relativity of Simultaneity (for certain events, the sequence in which they occur is dependent on the observer)
- Nothing can move faster than the speed of light (we shall denote the value of the speed of light as cc)

Why is there a mixing between space and time? In order to examine this we must know the founding principles of relativity. They are:

1. The Principle of Relativity: The laws of physics for *observers* which are not accelerating relative to one another should be the same.
2. The Principle of Invariant Light Speed: All observers, moving at constant speed, measure the same speed of light regardless of how fast they are moving.

If one accepts the second principle as fact then it immediately follows that space and time are not independent. Why? Let us look at the experiment in in which there is a light source, a fixed observer, and a rocket ship moving toward the light source. The two observers *are related by a coordinate , or space-time, transformation.* The second principle then tells us that no matter how fast the rocket is moving, both observers must measure the same light speed emanating from the source. The only way this can happen is if the clock of the rocket observer is ticking at a different rate than the stationary observer. How much different? This can be expressed in the time dilation equation:



Measuring Light: A stationary observer will measure the same speed of light as an observer who is moving in a rocket ship even if that rocket is moving close to light speed.

$$\mathrm{t_s} = \frac{\mathrm{t_m}}{\sqrt{1-\left(\frac{\mathrm{v}^2}{\mathrm{c}^2}\right)}} \tag{7.4.1}$$

Where tsts is the time elapsed for the stationary observer, tmtm is the time elapsed for the moving observer, and vv is the velocity of the rocket as *measured from the stationary frame*. One can then see that as $V \rightarrow C$ then the time elapsed in the stationary frame goes to infinity. To place some numbers, let $v = 0.99986c$, and $t_m = 1$ sec . The time elapsed in the stationary frame is then one hour. Thus for every second lived in the rocket, the stationary man lives one hour!

One of the more radical results of time dilation is the so-called "twin paradox. " The twin paradox is a thought experiment in special relativity that involves identical twins. One of the twins goes on a journey into space in a rocket that has a velocity near the speed of light. Upon returning home the twin finds that the twin that remained on Earth has aged more. This consequence altered the perception that aging is necessarily constant.

The square root factor in the time dilation equation is very important and we denote it as:

This factor shows up frequently in special relativity. For example the length contraction formula is:

$$L = L_0 \sqrt{1 - \left(\frac{v}{c}\right)} = \frac{L_0}{\gamma} \tag{7.4.2}$$

where L_0 is the rest length, the length of an object measured in the co-moving frame of the object, and L is the length of the object as measured by the observer who sees the object moving at speed v. In our rocket example, the stationary observer measures the length of the rocket as being less than what someone who was moving with the rocket would measure. This altered the perception that the length of an object would appear the same regardless of the reference frame of the observer.

Another radical finding that was made possible by the discovery of special relativity is the equivalence of energy and mass. Combined with other laws of physics, the postulates of special relativity predict that mass and energy are related by: $E = mc^2$, where c is the speed of light in vacuum. This altered the perception that mass and energy are completely different things and paved the way for nuclear power and nuclear weapons.

As a final note it is important to note how big the speed of light is compared to every day life. The speed of light is:

$$c = 3 \times 10^8 \mathrm{m/s} \tag{7.4.3}$$

Thus in every day life $\gamma \approx 1$ and we do not experience significant time dilation or length contraction. If we did, life would be very different.

Four-Dimensional Space-Time

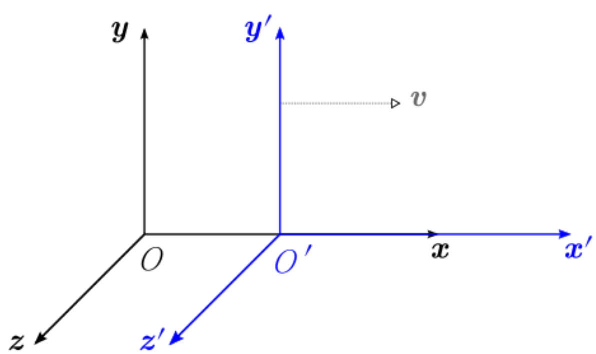
We live in four-dimensional space-time, in which the ordering of certain events can depend on the observer.

learning objectives

- Formulate major results of special relativity

Working in Four Dimensions

Let us examine two observers who are moving relative to one another at a constant velocity. We shall denote them as observer A and observer A'. Observer A sets up a space-time coordinate system (t, x, y, z); similarly, A' sets up his own space-time coordinate system (t', x', y', z'). (See for an example.) Therefore both observers live in a four-dimensional world with three space dimensions and one time dimension.



Two Coordinate Systems: Two coordinate systems in which the primed frame moves with velocity v with respect to the unprimed frame

You should not find it odd to work with four dimensions; any time you have to meet your friend somewhere you have to tell him four variables: where (three spatial coordinates) and when (one time coordinate). In other words, we have always lived in four dimensions, but so far you have probably thought of space and time as completely separate.

The Movement of Light in Four Dimensions

Back to our example: let us assume that at some point in space-time there is a beam of light that emerges. Both observers measure how far the beam has traveled at each point in time and how long it took to travel to travel that distance. That is to say, observer A measures:

$(\Delta \mathrm{t}, \Delta \mathrm{x}, \Delta \mathrm{y}, \Delta \mathrm{z})$

where, for example, $\Delta \mathrm{t}=\mathrm{t}-\mathrm{t}_0$; t is the time at which the measurement took place; and t_0 is the time at which the light was turned on.

Similarly, observer A' measures:

$(\Delta t', \Delta x', \Delta y', \Delta z')$

where we set up the system such that both observers agree on $(\mathrm{t}_0, \mathrm{x}_0, \mathrm{y}_0, \mathrm{z}_0)$. Due to the invariance of the speed of light both observers will agree on:

$$\frac{\Delta \mathrm{X}^2+\Delta \mathrm{Y}^2+\Delta \mathrm{Z}^2}{\Delta \mathrm{T}^2}=\mathrm{c}^2 \rightarrow 0=-\mathrm{c}^2 \Delta \mathrm{T}^2+\Delta \mathrm{X}^2+\Delta \mathrm{Y}^2+\Delta \mathrm{Z}^2 \tag{7.4.4}$$

where $(\mathrm{T}, \mathrm{X}, \mathrm{Y}, \mathrm{Z})$refers to the coordinates in either frame. Therefore there is a specific rule that all light paths must follow. For general events we can define the quantity:

$$\mathrm{s}^2=-\mathrm{c}^2 \Delta t^2+\Delta \mathrm{x}^2+\Delta \mathrm{y}^2+\Delta \mathrm{z}^2 \tag{7.4.5}$$

This is known as the line element and is the same for all observers. (Using the principles of relativity, you can prove this for general separations, not just light rays). The set of all coordinate transformations that leave the above quantity invariant are known as Lorentz Transformations. It follows that the coordinate systems of all physical observers are related to each other by Lorentz Transformations. (The set of all Lorentz transformations form what mathematicians call a group, and the study of group theory has revolutionized physics). For the coordinate transformation in, the transformations are:

$$\begin{aligned}
& \mathrm{t}'=\gamma\left(\mathrm{t}-\mathrm{vx}/\mathrm{c}^2\right) \\
& \mathrm{x}'=\gamma(\mathrm{x}-\mathrm{vt}) \\
& \mathrm{y}'=\mathrm{y} \\
& \mathrm{z}'=\mathrm{z}
\end{aligned} \tag{7.4.6}$$

where

$$\gamma=\frac{1}{\sqrt{1-(\mathrm{v}/\mathrm{c})^2}} \tag{7.4.7}$$

We define the separation between space-time points as follows:

$$\mathrm{s}^2>0: \text{ space-like} \tag{7.4.8}$$

$$\mathrm{s}^2<0: \text{ time-like} \tag{7.4.9}$$

$$\mathrm{s}^2=0: \text{ null} \tag{7.4.10}$$

We separate these events because they are very different. For example, for a space-like separation you can always find a coordinate transformation that reverses the time-ordering of the events (try to prove this for the example in). This phenomenon is known as the relativity of simultaneity and may be counterintuitive.

Space-Like Space-Time Separations

Let us examine two car crashes, one in New York and one in London, such that they occur in the same time in one frame. In this situation, the space-time separation between the two events is space-like. The question of whether the events are simultaneous is relative: in some reference frames the two accidents may happen at the same time; in other frames (in a different state of motion relative to the events) the crash in London may occur first; and in still other frames the New York crash may occur first. (In practice, this does not affect us because the frames that switch the order of the events must move at unreachably high speeds.)

Time-Like and Null Space-Time Separations

Events that are time-like or null do not share this property, and therefore there is a causal ordering between time-like events. In other words, if two events are time-like separated, then they can effect each other. The reason is that if two space-time points are time-like or null separated, one can always send a light signal from one point to another.

Special Relativity

Finally, let's discuss an important result of special relativity — that the energy EE of an object moving with speed vv is:

$$\mathrm{E}=\frac{\mathrm{m}_0 \mathrm{c}^2}{\sqrt{1-(\mathrm{v}/\mathrm{c})^2}}=\mathrm{mc}^2 \tag{7.4.11}$$

where m0m0 is the mass of the object at rest and m=γm0m=γm0 is the mass when the object is moving. The above formula immediately shows why it is impossible to travel faster than the speed of light. As $\mathrm{v} \rightarrow \mathrm{c}, \mathrm{m} \rightarrow \infty$, and it takes an infinite amount of energy to accelerate the object further.

The Relativistic Universe

Gravity is a geometrical effect in which a metric matrix plays a special role, and the motion of objects are altered by curved space.

learning objectives

- Identify factors that affect motion near massive objects

Relativity

Special relativity indicates that humans live in a four-dimensional space-time where the 'distance' ssbetween points in space-time can be regarded as:

\[\mathrm{ s } ^ { 2 } = - \mathrm { c } ^ { 2 } \Delta \mathrm { t } ^ { 2 } + \Delta \mathrm { x } ^ { 2 } + \Delta \mathrm{ y } ^ { 2 } + \Delta \mathrm { z } ^ { 2 } = \mathrm{ X } ^ { \mathrm { T } } \eta \mathrm{ X }

The last equation is a matrix relation in which TT denotes transpose (for vectors $\mathrm{A}^{\mathrm{T}}\mathrm{B}=\mathrm{A}\cdot\mathrm{B}$), X is the vector \)(\mathrm { c } \Delta \mathrm { t } , \Delta \mathrm { x } , \Delta \mathrm { y } , \Delta \mathrm { z })\), and η is the matrix:

$$\eta=\begin{pmatrix}-1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\end{pmatrix} \tag{7.4.12}$$

A matrix that goes in between two vectors to give a length is called a metric. In mathematics, a metric or distance function is a function which defines a distance between elements of a set. In this case, the set is the space-time and the elements are points in that space-time. A space-time with the ηη metric is called Minkowski space and ηη is the Minkowski metric.

Four-dimensional Minkowski space-time is only one of many different possible space-times (geometries) which differ in their metric matrix. An arbitrary metric matrix can be denoted as gg, raising questions as to what space-times with different metrics represent. In 1916, Einstein found the importance of these space-times in his theory of general relativity.

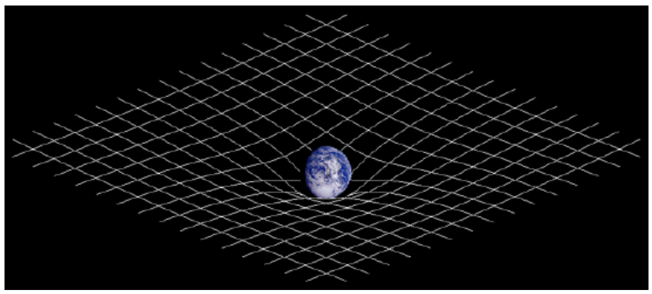
General Relativity

General relativity, or the general theory of relativity, is the geometric theory of gravitation published by Albert Einstein in 1916. It is the current description of gravitation in modern physics. General relativity generalizes special relativity and Newton's law of universal gravitation, providing a unified description of gravity as a geometric property of space and time, or space-time. In particular, the curvature of space-time is directly related to the energy and momentum of whatever matter and radiation are present. The relation is specified by the Einstein field equations, a system of partial differential equations.

$$\mathrm{g} \leftrightarrow \text{ curvature } \leftrightarrow \text{ Energy and Momentum} \tag{7.4.13}$$

People can use the metric to calculate curvature and then use the Einstein field equations to relate the curvature to the energy and momentum of the space-time. Going in the reverse order, energy and momentum affect the curvature and the space-time. Thus, energy and momentum curves space-time. Minkowski space is the special space devoid of matter, and as a result, it is completely flat. The precise definition of curvature requires knowledge of advanced mathematics, but an intuitive way to understand it is that the definition of a straight line changes in curved spacetime.

A pictorial example is shown in the figure below, where anything that is near the Earth has its motion altered due to the curved space-time. This altering of motion affects satellites, the moon, and even humans. If the space around the Earth were flat, humans would simply float away if they jumped upwards. Since the Earth alters the space-time, humans are pulled toward the Earth. In essence, gravity is a geometrical effect.



Curvature of space-time: The massive Earth is altering the curvature of space-time.

Key Points

- Time is relative.
- Lengths of moving objects are different than if their lengths were measured in a co-moving frame.
- Time and space are not independent.
- We live in a four-dimensional universe; the first three dimensions are spatial, and the fourth is time.
- The coordinate system of physical observers are related to one another via Lorentz transformations.
- Nothing can travel faster than the speed of light.
- The metric matrix can be used to calculate the curvature of space-time.
- Curvature can be related to energy and momentum via the Einstein equations.
- Due to the curvature of space-time, the motion of objects are altered near massive objects.

Key Terms

- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **time dilation**: The slowing of the passage of time experienced by objects in motion relative to an observer; measurable only at relativistic speeds.
- **length contraction**: Observers measure a moving object's length as being smaller than it would be if it were stationary.
- **line element**: An invariant quantity in special relativity
- **Lorentz transformation**: a transformation relating the spacetime coordinates of one frame of reference to another in special relativity
- **relativity of simultaneity**: For space-like separated space-time points, the time-ordering between events is relative.
- **general relativity**: A theory extending special relativity and uniformly accounting for gravity and accelerated frames of reference, postulating that space-time curves in the presence of mass.
- **Minkowski space**: A four dimensional flat space-time. Because it is flat, it is devoid of matter.
- **metric**: A metric, or distance function, is a function which defines a distance between elements of a set.

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CHAPTER OVERVIEW

8: Introduction to Quantum Physics

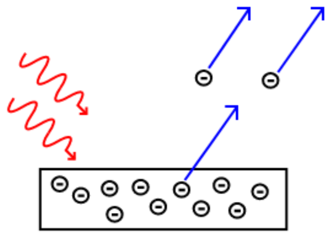
Topic hierarchy

8.1: History and Quantum Mechanical Quantities

learning objectives

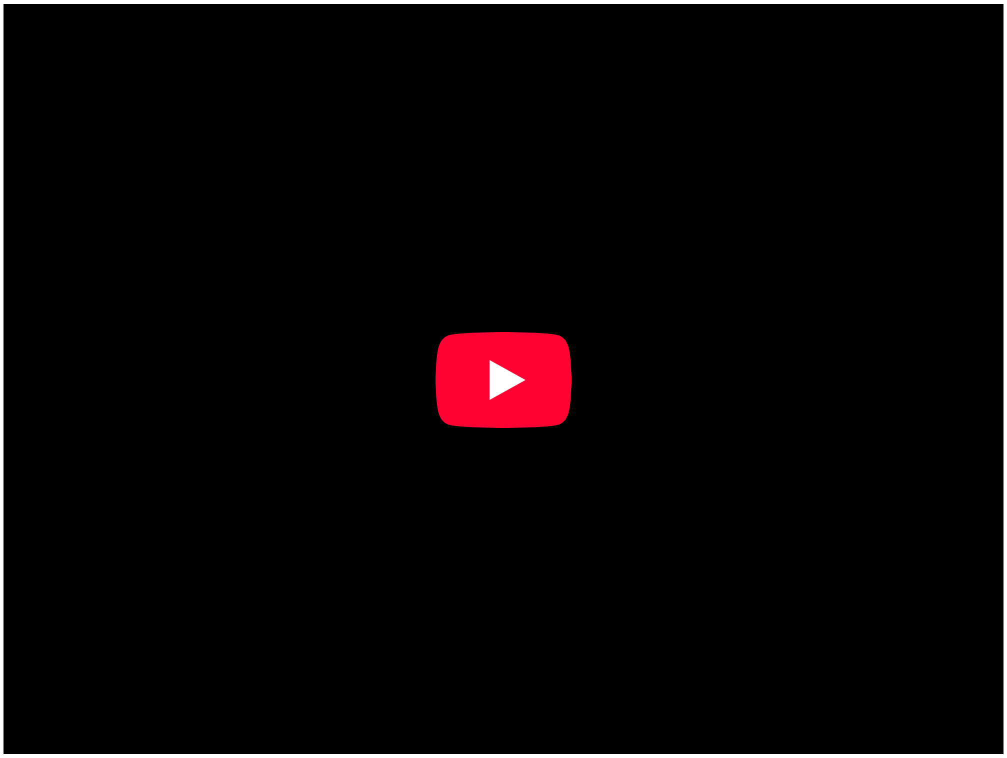
- Explain how the photoelectric effect paradox was solved by Albert Einstein.

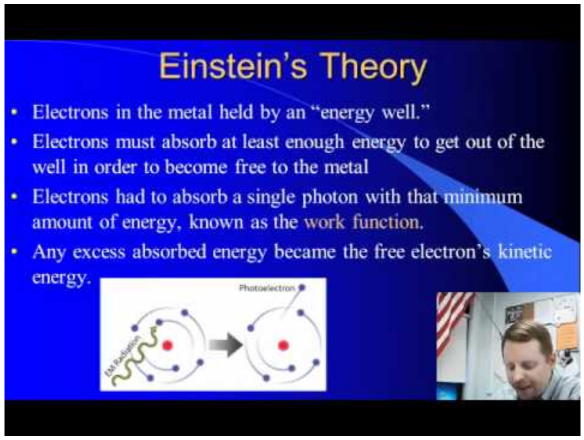
Electrons are emitted from matter when light shines on a surface . This is called the photoelectric effect, and the electrons emitted in this manner are called photoelectrons.



The Photoelectric Effect: Electrons are emitted from matter by absorbed light.

The photoelectric effect typically requires photons with energies from a few electronvolts to 1 MeV for heavier elements, roughly in the ultraviolet and X-ray range. Study of the photoelectric effect led to important steps in understanding the quantum nature of light and electrons and influenced the formation of the concept of wave-particle duality. The photoelectric effect is also widely used to investigate electron energy levels in matter.





Photoelectric Effect: A brief introduction to the Photoelectric Effect and electron photoemission.

Heinrich Hertz discovered the photoelectric effect in 1887. Although electrons had not been discovered yet, Hertz observed that electric currents were produced when ultraviolet light was shined on a metal. By the beginning of the 20th century, physicists confirmed that:

- The energy of the individual photoelectrons increased with the frequency (or color) of the light, but was independent of the intensity (or brightness) of the radiation.
- The photoelectric current was determined by the light's intensity; doubling the intensity of the light doubled the number of emitted electrons.

This observation was very puzzling to many physicists. At the time, light was accepted as a wave phenomenon. Since energy carried by a wave should only depend on its amplitude (and not on the frequency of the wave), the frequency dependence of the emitted electrons' energies didn't make sense.

In 1905, Albert Einstein solved this apparent paradox by describing light as composed of discrete quanta (now called photons), rather than continuous waves. Building on Max Planck's theory of black body radiation, Einstein theorized that the energy in each quantum of light was equal to the frequency multiplied by a constant h, later called Planck's constant. A photon above a threshold frequency has the required energy to eject a single electron, creating the observed effect. As the frequency of the incoming light increases, each photon carries more energy, hence increasing the energy of each outgoing photoelectron. By doubling the number of photons as the intensity is doubled, the number of photelectrons should double accordingly.

According to Einstein, the maximum kinetic energy of an ejected electron is given by $\mathrm{K_{max}} = \mathrm{hf} - \phi$, where h is the Planck constant and f is the frequency of the incident photon. The term ϕ is known as the work function, the minimum energy required to remove an electron from the surface of the metal. The work function satisfies $\phi = \mathrm{hf_0}$, where $\mathrm{f_0}$ is the threshold frequency for the metal for the onset of the photoelectric effect. The value of work function is an intrinsic property of matter.

Is light then composed of particles or waves? Young's experiment suggested that it was a wave, but the photoelectric effect indicated that it should be made of particles. This question would be resolved by de Broglie: light, and all matter, have both wave-like and particle-like properties.

Photon Energies of the EM Spectrum

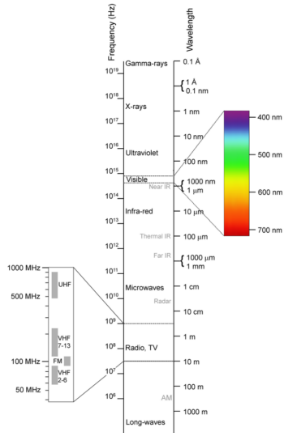
The electromagnetic (EM) spectrum is the range of all possible frequencies of electromagnetic radiation.

learning objectives

- Compare photon energy with the frequency of the radiation

The Electromagnetic Spectrum

The electromagnetic (EM) spectrum is the range of all possible frequencies of electromagnetic radiation . The electromagnetic spectrum extends from below the low frequencies used for modern radio communication to gamma radiation at the short-wavelength (high-frequency) end, thereby covering wavelengths of thousands of kiilometers down to those of a fraction of the size of an atom (approximately an angstrom). The limit for long wavelengths is the size of the universe itself.



Electromagnetic spectrum: This shows the electromagnetic spectrum, including the visible region, as a function of both frequency (left) and wavelength (right).

Maxwell's equations predicted an infinite number of frequencies of electromagnetic waves, all traveling at the speed of light. This was the first indication of the existence of the entire electromagnetic spectrum. Maxwell's predicted waves included waves at very low frequencies compared to infrared, which in theory might be created by oscillating charges in an ordinary electrical circuit of a certain type. In 1886, the physicist Hertz built an apparatus to generate and detect what are now called radio waves, in an attempt to prove Maxwell's equations and detect such low-frequency electromagnetic radiation. Hertz found the waves and was able to infer (by measuring their wavelength and multiplying it by their frequency) that they traveled at the speed of light. Hertz also demonstrated that the new radiation could be both reflected and refracted by various dielectric media, in the same manner as light.

Filling in the Electromagnetic Spectrum

In 1895, Wilhelm Röntgen noticed a new type of radiation emitted during an experiment with an evacuated tube subjected to a high voltage. He called these radiations 'X-rays' and found that they were able to travel through parts of the human body but were reflected or stopped by denser matter such as bones. Before long, there were many new uses for them in the field of medicine.

The last portion of the electromagnetic spectrum was filled in with the discovery of gamma rays. In 1900, Paul Villard was studying the radioactive emissions of radium when he identified a new type of radiation that he first thought consisted of particles similar to known alpha and beta particles, but far more penetrating than either. However, in 1910, British physicist William Henry Bragg demonstrated that gamma rays are electromagnetic radiation, not particles. In 1914, Ernest Rutherford (who had named them gamma rays in 1903 when he realized that they were fundamentally different from charged alpha and beta rays) and Edward Andrade measured their wavelengths, and found that gamma rays were similar to X-rays, but with shorter wavelengths and higher frequencies.

The relationship between photon energy and the radiation's frequency and wavelength is illustrated as the following equilavent equation: $\nu = \frac{c}{\lambda}$, or $\nu = \frac{\mathrm{E}}{\mathrm{h}}$ or $\mathrm{E} = \frac{\mathrm{hc}}{\lambda}$ where vv is the frequency, λ is the wavelength, E is photon energy, c is the speed of light, and hh is the Planck constant. Generally, electromagnetic radiation is classified by wavelength into radio waves, microwaves, terahertz (or sub-millimeter) radiation, infrared, the visible region humans perceive as light, ultraviolet, X-rays, and gamma rays. The behavior of EM radiation depends on its wavelength. When EM radiation interacts with single atoms and molecules, its behavior also depends on the amount of energy per quantum (photon) it carries.

Most parts of the electromagnetic spectrum are used in science for spectroscopic and other probing interactions as ways to study and characterize matter. Also, radiation from various parts of the spectrum has many other uses in communications and manufacturing.

Energy, Mass, and Momentum of Photon

A photon is an elementary particle, the quantum of light, which carries momentum and energy.

learning objectives

- State physical properties of a photon

A photon is an elementary particle, the quantum of light. It has no rest mass and has no electric charge. The modern photon concept was developed gradually by Albert Einstein to explain experimental observations of the photoelectric effect, which did not fit the classical wave model of light. In particular, the photon model accounted for the frequency dependence of light's energy. Max Planck explained black body radiation using semiclassical models, in which light is still described by Maxwell's equations, but the material objects that emit and absorb light, do so in amounts of energy that are quantized.

Photons are emitted in many natural processes. They are emitted from light sources such as floor lamps or lasers . For example, when a charge is accelerated it emits photons, a phenomenon known as synchrotron radiation. During a molecular, atomic or nuclear transition to a lower or higher energy level, photons of various energy will be emitted or absorbed respectively. A photon can also be emitted when a particle and its corresponding antiparticle are annihilated. During all these processes, photons will carry energy and momentum.

laser: Photons emitted in a coherent beam from a laser.

Energy of photon: From the studies of photoelectric effects, energy of a photon is directly proportional to its frequency with the Planck constant being the proportionality factor. Therefore, we already know that $\mathrm{E} = \mathrm{h}\nu$ (Eq. 1), where E is the energy and νν is the frequency.

Momentum of photon: According to the theory of Special Relativity, energy and momentum (p) of a particle with rest mass m has the following relationship: $\mathrm{E}^2 = \left(\mathrm{mc}^2\right)^2 + \mathrm{p}^2\mathrm{c}^2$, where c is the speed of light. In the case of a photon with zero rest mass, we get $\mathrm{E} = \mathrm{pc}$. Combining this with Eq. 1, we get $\mathrm{p} = \frac{\mathrm{h}\nu}{\mathrm{c}} = \frac{\mathrm{h}}{\lambda}$. Here, λ is the wavelength of the light. Since momentum is a vector quantity and p points in the direction of the photon's propagation, we can write $\mathrm{p} = \mathrm{hk}$, where $\mathrm{h} = \frac{\mathrm{h}}{2\pi}$ and is k a wave vector.

You may wonder how an object with zero rest mass can have nonzero momentum. This confusion often arises because of the commonly used form of momentum (mvmv in non-relativistic mechanics and γmvγmv in relativistic mechanics, where vv is velocity and $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$.) This formula, obviously, shouldn't be used in the case $\mathrm{v} = \mathrm{c}$.

Implications of Quantum Mechanics

Quantum mechanics has had enormous success in explaining microscopic systems and has become a foundation of modern science and technology.

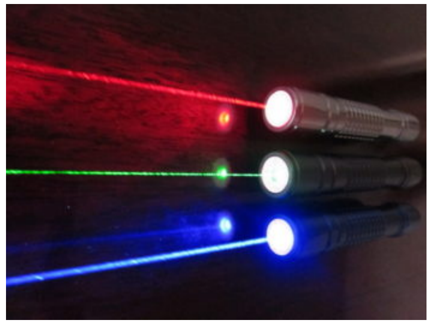
learning objectives

- Explain importance of quantum mechanics for technology and other branches of science

The field of quantum mechanics has been enormously successful in explaining many of the features of our world. The behavior of the subatomic particles (electrons, protons, neutrons, photons, and others) that make up all forms of matter can often be satisfactorily described only using quantum mechanics. Quantum mechanics has also strongly influenced string theory.

Quantum mechanics is also critically important for understanding how individual atoms combine covalently to form molecules. The application of quantum mechanics to chemistry is known as quantum chemistry. Relativistic quantum mechanics can, in principle, mathematically describe most of chemistry. Quantum mechanics can also provide quantitative insight into ionic and covalent bonding processes by explicitly showing which molecules are energetically favorable to which other molecules and the magnitudes of the energies involved. Furthermore, most of the calculations performed in modern computational chemistry rely on quantum mechanics.

A great number of modern technological inventions operate on a scale where quantum effects are significant. Examples include the laser , the transistor (and thus the microchip), the electron microscope, and magnetic resonance imaging (MRI). The study of semiconductors led to the invention of the diode and the transistor, which are indispensable parts of modern electronic systems and devices.



Laser: Red (635-nm), green (532-nm), and blue-violet (445-nm) lasers

Researchers are currently seeking robust methods of directly manipulating quantum states. Efforts are being made to more fully develop quantum cryptography, which will theoretically allow guaranteed secure transmission of information. A more distant goal is the development of quantum computers, which are expected to perform certain computational tasks exponentially faster than classical computers. Another topic of active research is quantum teleportation, which deals with techniques to transmit quantum information over arbitrary distances.

Particle-Wave Duality

Wave–particle duality postulates that all physical entities exhibit both wave and particle properties.

learning objectives

- Describe experiments that demonstrated wave-particle duality of physical entities

Wave–particle duality postulates that all physical entities exhibit both wave and particle properties. As a central concept of quantum mechanics, this duality addresses the inability of classical concepts like "particle" and "wave" to fully describe the behavior of (usually) microscopic objects.

From a classical physics point of view, particles and waves are distinct concepts. They are mutually exclusive, in the sense that a particle doesn't exhibit wave-like properties and vice versa. Intuitively, a baseball doesn't disappear via destructive interference, and our voice cannot be localized in space. Why then is it that physicists believe in wave-particle duality? Because that's how mother Nature operates, as they have learned from several ground-breaking experiments. Here is a short, chronological list of those experiments:

- Young's double-slit experiment: In the early Nineteenth century, the double-slit experiments by Young and Fresnel provided evidence that light is a wave. In 1861, James Clerk Maxwell explained light as the propagation of electromagnetic waves according to the Maxwell's equations.
- Black body radiation: In 1901, to explain the observed spectrum of light emitted by a glowing object, Max Planck assumed that the energy of the radiation in the cavity was quantized, contradicting the established belief that electromagnetic radiation is a wave.
- Photoelectric effect: Classical wave theory of light also fails to explain photoelectric effect. In 1905, Albert Einstein explained the photoelectric effects by postulating the existence of photons, quanta of light energy with particulate qualities.
- De Broglie's wave (matter wave): In 1924, Louis-Victor de Broglie formulated the de Broglie hypothesis, claiming that all matter, not just light, has a wave-like nature. His hypothesis was soon confirmed with the observation that electrons (matter) also displays diffraction patterns, which is intuitively a wave property.

From these historic achievements, physicists now accept that all entities in nature behave as both a particle and a wave, depending on the specifics of the phenomena under consideration. Because of its counter-intuitive aspect, the meaning of the particle-wave duality is still a point of debate in quantum physics. The standard interpretation is that the act of measurement causes the set of probabilities, governed by a probability distribution function acquired from a "wave", to immediately and randomly assume one of the possible values, leading to a "particle"-like result.

So, why do we not notice a baseball acting like a wave? The wavelength of the matter wave associated with a baseball, say moving at 95 miles per hour, is extremely small compared to the size of the ball so that wave-like behavior is never noticeable.

Diffraction Revisited

De Broglie's hypothesis was that particles should show wave-like properties such as diffraction or interference.

learning objectives

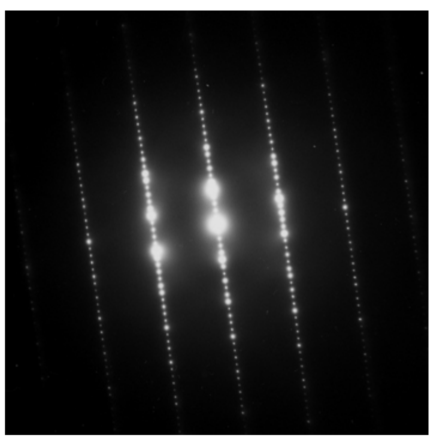
- Compare application of X-ray, electron, and neutron diffraction for materials research

The de Broglie hypothesis, formulated in 1924, predicts that particles should also behave as waves. The wavelength of an electron is given by the de Broglie equation $\lambda = \frac{h}{p}$. Here h is Planck's constant and pp the relativistic momentum of the electron. λ is called the de Broglie wavelength.

From the work by Planck (black body radiation) and Einstein (photoelectric effect), physicists understood that electromagnetic waves sometimes behaved like particles. De Broglie's hypothesis is complementary to this idea: particles should also show wave-like properties such as diffraction or interference. De Broglie's formula was confirmed three years later for electrons (which have a rest-mass) with the observation of electron diffraction in two independent experiments. George Paget Thomson passed a beam of electrons through a thin metal film and observed the predicted interference patterns. Clinton Joseph Davisson and Lester Halbert Germerguided their beam through a crystalline grid to observe diffraction patterns.

X-ray diffraction is a commonly used tool in materials research. Thanks to the wave-particle duality, matter wave diffraction can also be used for this purpose. The electron, which is easy to produce and manipulate, is a common choice. A neutron is another particle of choice. Due to the different kinds of interactions involved in the diffraction processes, the three types of radiation (X-ray, electron, neutron) are suitable for different kinds of studies.

Electron diffraction is most frequently used in solid state physics and chemistry to study the crystalline structure of solids. Experiments are usually performed using a transmission electron microscope or a scanning electron microscope. In these instruments, electrons are accelerated by an electrostatic potential in order to gain the desired energy and, thus, wavelength before they interact with the sample to be studied. The periodic structure of a crystalline solid acts as a diffraction grating, scattering the electrons in a predictable manner. Working back from the observed diffraction pattern, it is then possible to deduce the structure of the crystal producing the diffraction pattern. Unlike other types of radiation used in diffraction studies of materials, such as X-rays and neutrons, electrons are charged particles and interact with matter through the Coulomb forces. This means that the incident electrons feel the influence of both the positively charged atomic nuclei and the surrounding electrons. In comparison, X-rays interact with the spatial distribution of the valence electrons, while neutrons are scattered by the atomic nuclei through the strong nuclear force.



Electron Diffraction Pattern: Typical electron diffraction pattern obtained in a transmission electron microscope with a parallel electron beam.

Neutrons have also been used for studying crystalline structures. They are scattered by the nuclei of the atoms, unlike X-rays, which are scattered by the electrons of the atoms. Thus, neutron diffraction has some key differences compared to more common methods using X-rays or electrons. For example, the scattering of X-rays is highly dependent on the atomic number of the atoms (i.e., the number of electrons), whereas neutron scattering depends on the properties of the nuclei. In addition, the magnetic moment of the neutron is non-zero, and can thus also be scattered by magnetic fields. This means that neutron scattering is more useful for determining the properties of atomic nuclei, despite the fact that neutrons are significantly harder to create, manipulate, and detect compared to X-rays and electrons.

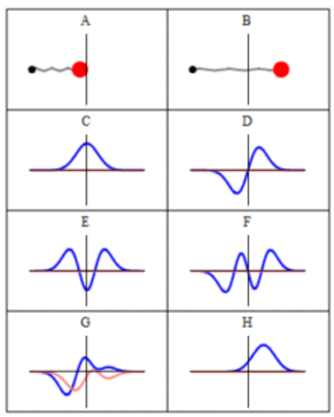
The Wave Function

A wave function is a probability amplitude in quantum mechanics that describes the quantum state of a particle and how it behaves.

learning objectives

- Relate the wave function with the probability density of finding a particle, commenting on the constraints the wave function must satisfy for this to make sense

In quantum mechanics, a wave function is a probability amplitude describing the quantum state of a particle and how it behaves. Typically, its values are complex numbers. For a single particle, it is a function of space and time. The most common symbols for a wave function are $\psi(x)$ or $\Psi(x)$ (lowercase or uppercase psi, respectively), when the wave function is given as a function of position x. Although ψ is a complex number, $|\psi|2$ is a real number and corresponds to the probability density of finding a particle in a given place at a given time, if the particle's position is measured.



Trajectories of a Harmonic Oscillator: This figure shows some trajectories of a harmonic oscillator (a ball attached to a spring) in classical mechanics (A-B) and quantum mechanics (C-H). In quantum mechanics (C-H), the ball has a wave function, which is shown with its real part in blue and its imaginary part in red. The trajectories C-F are examples of standing waves, or "stationary states. " Each standing-wave frequency is proportional to a possible energy level of the oscillator. This "energy quantization" does not occur in classical physics, where the oscillator can have any energy.

The laws of quantum mechanics (the Schrödinger equation) describe how the wave function evolves over time. The wave function behaves qualitatively like other waves, such as water waves or waves on a string, because the Schrödinger equation is mathematically a type of wave equation. This explains the name "wave function" and gives rise to wave-particle duality.

The wave function must satisfy the following constraints for the calculations and physical interpretation to make sense:

- It must everywhere be finite.
- It must everywhere be a continuous function and continuously differentiable.
- It must everywhere satisfy the relevant normalization condition so that the particle (or system of particles) exists somewhere with 100-percent certainty.

If these requirements are not met, it's not possible to interpret the wave function as a probability amplitude. This is because the values of the wave function and its first order derivatives may not be finite and definite (having exactly one value), which means that the probabilities can be infinite and have multiple values at any one position and time, which is nonsense. Furthermore, when we use the wave function to calculate an observation of the quantum system without meeting these requirements, there will not be finite or definite values to use (in this case the observation can take a number of values and can be infinite). This is not a possible occurrence in a real-world experiment. Therefore, a wave function is meaningful only if these conditions are satisfied.

de Broglie and the Wave Nature of Matter

The concept of “matter waves” or “de Broglie waves” reflects the wave-particle duality of matter.

learning objectives

- Formulate the de Broglie relation as an equation

In quantum mechanics, the concept of matter waves (or de Broglie waves) reflects the wave-particle duality of matter. The theory was proposed by Louis de Broglie in 1924 in his PhD thesis. The de Broglie relations show that the wavelength is inversely proportional to the momentum of a particle, and is also called de Broglie wavelength.

Einstein derived in his theory of special relativity that the energy and momentum of a photon has the following relationship:

$\mathrm{E}=\mathrm{pc}$ (E: energy, p: momentum, c: speed of light).

He also demonstrated, in his study of photoelectric effects, that energy of a photon is directly proportional to its frequency, giving us this equation:

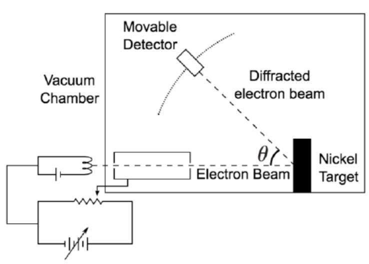
$\mathrm{E}=\mathrm{h}\nu$ (h: Planck constant, ν: frequency).

Combining the two equations, we can derive a relationship between the momentum and wavelength of light:

$\mathrm{p}=\frac{\mathrm{E}}{\mathrm{c}}=\frac{\mathrm{h}\nu}{\mathrm{c}}=\frac{\mathrm{h}}{\lambda}$. Therefore, we arrive at $\lambda=\frac{\mathrm{h}}{\mathrm{p}}$.

De Broglie’s hypothesis is that this relationship $\lambda=\mathrm{hp}$, derived for electromagnetic waves, can be adopted to describe matter (e.g. electron, neutron, etc.) as well.

De Broglie didn’t have any experimental proof at the time of his proposal. It took three years for Clinton Davisson and Lester Germer to observe diffraction patterns from electrons passing a crystalline metallic target (see). Before the acceptance of the de Broglie hypothesis, diffraction was a property thought to be exhibited by waves only. Therefore, the presence of any diffraction effects by matter demonstrated the wave-like nature of matter. This was a pivotal result in the development of quantum mechanics. Just as the photoelectric effect demonstrated the particle nature of light, the Davisson–Germer experiment showed the wave-nature of matter, thus completing the theory of wave-particle duality.



Davisson-Germer Experimental Setup: The experiment included an electron gun consisting of a heated filament that released thermally excited electrons, which were then accelerated through a potential difference (giving them a certain amount of kinetic energy towards the nickel crystal). To avoid collisions of the electrons with other molecules on their way towards the surface, the experiment was conducted in a vacuum chamber. To measure the number of electrons that were scattered at different angles, an electron detector that could be moved on an arc path about the crystal was used. The detector was designed to accept only elastically scattered electrons.

Experiments with Fresnel diffraction and specular reflection of neutral atoms confirm the application to atoms of the de Broglie hypothesis. Further, recent experiments confirm the relations for molecules and even macromolecules, normally considered too large to undergo quantum mechanical effects. In 1999, a research team in Vienna demonstrated diffraction for molecules as large as fullerenes. The researchers calculated a De Broglie wavelength of the most probable C_{60} velocity as 2.5 pm.

The Heisenberg Uncertainty Principle

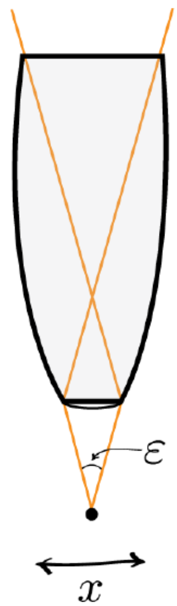
The uncertainty principle asserts a basic limit to the precision with which some physical properties of a particle can be known simultaneously.

learning objectives

- Relate the Heisenberg uncertainty principle with the matter wave nature of all quantum objects

The uncertainty principle is any of a variety of mathematical inequalities, asserting a fundamental limit to the precision with which certain pairs of physical properties of a particle, such as position x and momentum pp or energy E and time t, can be known simultaneously. The more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa. This can be formulated as the following inequality: $\sigma_{\mathrm{x}}\sigma_{\mathrm{y}} \geq \frac{\bar{\mathrm{h}}}{2}$, where σ_{x} is the standard deviation of position, σp is the standard deviation of momentum, and $\bar{\mathrm{h}} = \frac{\mathrm{h}}{2\pi}$. The uncertainty principle is inherent in the properties of all wave-like systems, and it arises in quantum mechanics simply due to the matter wave nature of all quantum objects. Thus, the uncertainty principle actually states a fundamental property of quantum systems, and is not a statement about the observational success of current technology.

The principle is quite counterintuitive, so the early students of quantum theory had to be reassured that naive measurements to violate it were bound always to be unworkable. One way in which Heisenberg originally illustrated the intrinsic impossibility of violating the uncertainty principle is by using an imaginary microscope as a measuring device.



Heisenberg Microscope: Heisenberg's microscope, with cone of light rays focusing on a particle with angle ϵ He imagines an experimenter trying to measure the position and momentum of an electron by shooting a photon at it.

Example 8.1.1:

Example One

If the photon has a short wavelength and therefore a large momentum, the position can be measured accurately. But the photon scatters in a random direction, transferring a large and uncertain amount of momentum to the electron. If the photon has a long wavelength and low momentum, the collision does not disturb the electron's momentum very much, but the scattering will reveal its position only vaguely.

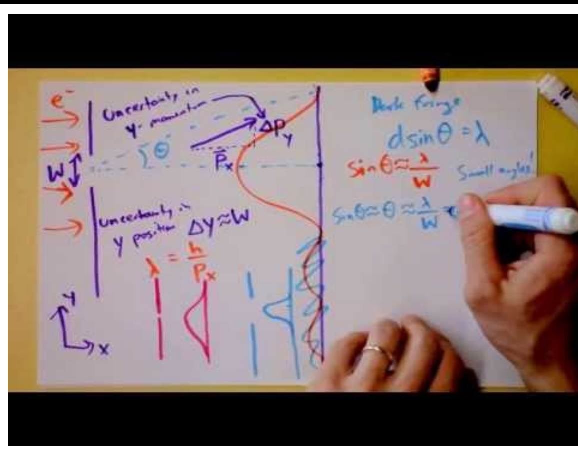
Example Two

If a large aperture is used for the microscope, the electron's location can be well resolved (see Rayleigh criterion); but by the principle of conservation of momentum, the transverse momentum of the incoming photon and hence the new momentum of the electron resolves poorly. If a small aperture is used, the accuracy of both resolutions is the other way around.

Heisenberg's Argument

Heisenberg's argument is summarized as follows. He begins by supposing that an electron is like a classical particle, moving in the xx direction along a line below the microscope, as in the illustration to the right. Let the cone of light rays leaving the microscope lens and focusing on the electron makes an angle εε with the electron. Let λ be the wavelength of the light rays. Then, according to the laws of classical optics, the microscope can only resolve the position of the electron up to an accuracy of $\delta \mathrm{x} = \frac{\lambda}{\sin(\varepsilon/2)}$ When an observer perceives an image of the particle, it's because the light rays strike the particle and bounce back through the microscope to their eye. However, we know from experimental evidence that when a photon strikes an electron, the latter has a recoil with momentum proportional to h/λ, where h is Planck's constant.

It is at this point that Heisenberg introduces objective indeterminacy into the thought experiment. He writes that "the recoil cannot be exactly known, since the direction of the scattered photon is undetermined within the bundle of rays entering the microscope". In particular, the electron's momentum in the xx direction is only determined up to δpx≈hλsin(ε/2)δpx≈hλsin(ε/2). Combining the relations for $\delta \mathrm{x}$ and $\delta \mathrm{p_x}$, we thus have that $\delta \mathbf{x} \cdot \delta \mathrm{p}_{\mathbf{x}} \approx \left(\frac{\lambda}{\sin(\varepsilon/2)}\right)\left(\frac{\mathrm{h}}{\lambda}\sin(\varepsilon/2)\right) = \mathrm{h}$, which is an approximate expression of Heisenberg's uncertainty principle.



Heisenberg Uncertainty Principle Derived and Explained

One of the most-oft quoted results of quantum physics, this doozie forces us to reconsider what we can know about the universe. Some things cannot be known simultaneously. In fact, if anything about a system is known perfectly, there is likely another characteristic that is completely shrouded in uncertainty. So significant figures ARE important after all!

Philosophical Implications

Since its inception, many counter-intuitive aspects of quantum mechanics have provoked strong philosophical debates.

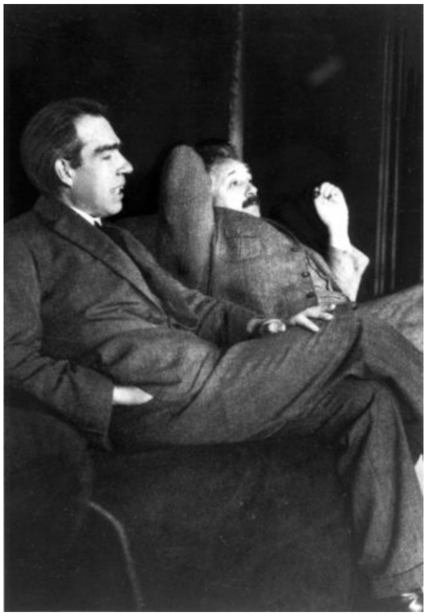
learning objectives

- Formulate the Copenhagen interpretation of the probabilistic nature of quantum mechanics

Since its inception, many counter-intuitive aspects and results of quantum mechanics have provoked strong philosophical debates and many interpretations. Even fundamental issues, such as Max Born's basic rules interpreting $\psi * \psi$ as a probability density function took decades to be appreciated by society and many leading scientists. Indeed, the renowned physicist Richard Feynman once said, "I think I can safely say that nobody understands quantum mechanics. "

The Copenhagen Interpretation

The Copenhagen interpretation—due largely to the Danish theoretical physicist Niels Bohr, shown in —remains a quantum mechanical formalism that is widely accepted amongst physicists, some 75 years after its enunciation. According to this interpretation, the probabilistic nature of quantum mechanics is not a temporary feature which will eventually be replaced by a deterministic theory, but instead must be considered a final renunciation of the classical idea of causality.



Niels Bohr and Albert Einstein: Niels Bohr (left) and Albert Einstein (right). Despite their pioneering contributions to the inception of the quantum mechanics, they disagreed on its interpretation.

The Copenhagen interpretation has philosophical implications to the concept of determinism. According to the theory of determinism, for everything that happens there are conditions such that, given those conditions, nothing else could happen. Determinism and free-will seem to be mutually exclusive. If the universe, and any person in it are governed by strict and universal laws , then that means that a person's behavior could be predicted based on sufficient knowledge of the circumstances obtained prior to that person's behavior. However, the Copenhagen interpretation suggests a universe in which outcomes are not fully determined by prior circumstances but also by probability. This gave thinkers alternatives to strictly bound possibilities, proposing a model for a universe that follows general rules but never had a predetermined future.

Philosophical Implications

It is also believed therein that any well-defined application of the quantum mechanical formalism must always make reference to the experimental arrangement. This is due to the quantum mechanical principle of wave function collapse. That is, a wave function which is initially in a superposition of several different possible states appears to reduce to a single one of those states after interaction with an observer. In simplified terms, it is the reduction of the physical possibilities into a single possibility as seen by an observer. This raises philosophical questions about whether something that is never observed actually exists.

Einstein-Podolsky-Rosen (EPR) Paradox

Albert Einstein (shown in , himself one of the founders of quantum theory) disliked this loss of determinism in measurement in the Copenhagen interpretation. Einstein held that there should be a local hidden variable theory underlying quantum mechanics and, consequently, that the present theory was incomplete. He produced a series of objections to the theory, the most famous of which has become known as the Einstein-Podolsky-Rosen (EPR) paradox. John Bell showed by Bell's theorem that this "EPR" paradox led to experimentally testable differences between quantum mechanics and local realistic theories. Experiments have been performed confirming the accuracy of quantum mechanics, thereby demonstrating that the physical world cannot be described by any local realistic theory. The Bohr-Einstein debates provide a vibrant critique of the Copenhagen Interpretation from an epistemological point of view.

Quantum Entanglement

One of the most bizarre aspect of the quantum mechanics is known as quantum entanglement. Quantum entanglement occurs when particles interact physically and then become separated, while isloated from the rest of the universe to prevent any deterioration of the quantum state. According to the Copenhagen interpretation of quantum mechanics, their shared state is indefinite until measured. Once a particle in the entangled state is measured and its state is determined, the Copenhagen interpretation demands that the other particles' state is also determined instantaneously. This bizarre nature of action at a distance (which seemingly violate the speed limit on the transmission of information implicit in the theory of relativity) is what bothered Einstein the most. (According to the theory of relativity, nothing can travel faster than the speed of light in a vacuum. This seemingly puts a limit on the speed at which information can be transmitted.) Quantum entanglement is the key element in proposals for quantum computers and quantum teleportation.

Key Points

- The energy of the emitted electrons depends only on the frequency of the incident light, and not on the light intensity.
- Einstein explained the photoelectric effect by describing light as composed of discrete particles.
- Study of the photoelectric effect led to important steps in understanding the quantum nature of light and electrons, which would eventually lead to the concept of wave-particle duality.
- Electromagnetic radiation is classified according to wavelength, divided into radio waves, microwaves, terahertz (or sub-millimeter) radiation, infrared, the visible region humans perceive as light, ultraviolet, X-rays, and gamma rays.
- Photon energy is proportional to the frequency of the radiation.
- Most parts of the electromagnetic spectrum are used in science for spectroscopic and other probing interactions as ways to study and characterize matter.
- $\mathrm{E}=\mathrm{hv}$ Energy of photon is proportional to its frequency.
- $\mathrm{p}=\mathrm{hk}$ Momentum of photon is proportional to the wave vector.
- Photon's rest mass is 0.
- A great number of modern technological inventions are based on quantum mechanics, including the laser, the transistor, the electron microscope, and magnetic resonance imaging.
- Quantum mechanics is also critically important for understanding how individual atoms combine covalently to form molecules. The application of quantum mechanics to chemistry is known as quantum chemistry.
- Researchers are currently seeking robust methods of directly manipulating quantum states for applications in computer and information science.
- All entities in Nature behave as both a particle and a wave, depending on the specifics of the phenomena under consideration.
- Particle-wave duality is usually hidden in macroscopic phenomena, conforming to our intuition.
- In the double-slit experiment of electrons, individual event displays a particle-like property of localization (or a "dot"). After many repetitions, however, the image shows an interference pattern, which indicates that each event is in fact governed by a probability distribution.
- The wavelength of an electron is given by the de Broglie equation $\lambda=\frac{\mathrm{h}}{\mathrm{p}}$.
- Because of different forms of interaction involved, X-ray, electron, and neutron are suitable for different studies of material properties.
- De Broglie's idea completed the wave-particle duality.
- $|\psi| 2(\mathrm{x})$ corresponds to the probability density of finding a particle in a given location x at a given time.
- The laws of quantum mechanics (the Schrödinger equation) describe how the wave function evolves over time. The Schrödinger equation is a type of wave equation, which explains the name "wave function".

- A wave function must satisfy a set of mathematical constraints for the calculations and physical interpretation to make sense.
- de Broglie relations show that the wavelength is inversely proportional to the momentum of a particle.
- The Davisson-Germer experiment demonstrated the wave-nature of matter and completed the theory of wave-particle duality.
- Experiments demonstrated that de Broglie hypothesis is applicable to atoms and macromolecules.
- The uncertainty principle is inherent in the properties of all wave-like systems, and that it arises in quantum mechanics is simply due to the matter wave nature of all quantum objects.
- The uncertainty principle is not a statement about the observational success of current technology.
- The more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa. This can be formulated as the following inequality: $\sigma_{\mathrm{X}}\sigma_{\mathrm{y}} \geq \frac{\bar{\mathrm{h}}}{2}$.
- According to the Copenhagen interpretation, the probabilistic nature of quantum mechanics is intrinsic in our physical universe.
- When quantum wave function collapse occurs, physical possibilities are reduced into a single possibility as seen by an observer.
- Once a particle in an entangled state is measured and its state is determined, the Copenhagen interpretation demands that the state of the other entangled particle is also determined instantaneously.

Key Terms

- **black body radiation**: The type of electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment, or emitted by a black body (an opaque and non-reflective body) held at constant, uniform temperature.
- **photoelectron**: Electrons emitted from matter by absorbing energy from electromagnetic radiation.
- **wave-particle duality**: A postulation that all particles exhibit both wave and particle properties. It is a central concept of quantum mechanics.
- **Planck constant**: a physical constant that is the quantum of action in quantum mechanics. It has a unit of angular momentum. The Planck constant was first described as the proportionality constant between the energy of a photon (unit of electromagnetic radiation) and the frequency of its associated electromagnetic wave in his derivation of the Planck's law
- **Maxwell's equations**: A set of equations describing how electric and magnetic fields are generated and altered by each other and by charges and currents.
- **elementary particle**: a particle not known to have any substructure
- **photoelectric effect**: The occurrence of electrons being emitted from matter (metals and non-metallic solids, liquids, or gases) as a consequence of their absorption of energy from electromagnetic radiation.
- **cryptography**: the practice and study of techniques for secure communication in the presence of third parties
- **relativistic quantum mechanics**: a theoretical framework for constructing quantum mechanical models of fields and many-body systems
- **string theory**: an active research framework in particle physics that attempts to reconcile quantum mechanics and general relativity
- **black body**: An idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. Although black body is a theoretical concept, you can find approximate realizations of black body in nature.
- **grating**: Any regularly spaced collection of essentially identical, parallel, elongated elements.
- **Schrödinger equation**: A partial-differential that describes how the quantum state of some physical system changes with time. It was formulated in late 1925 and published in 1926 by the Austrian physicist Erwin Schrödinger
- **harmonic oscillator**: a system that, when displaced from its equilibrium position, experiences a restoring force $\mathbf{F}$ proportional to the displacement x
- **diffraction**: The bending of a wave around the edges of an opening or an obstacle.
- **special relativity**: A theory that (neglecting the effects of gravity) reconciles the principle of relativity with the observation that the speed of light is constant in all frames of reference.
- **wave-particle duality**: A postulation that all particles exhibit both wave and particle properties. It is a central concept of quantum mechanics.
- **matter wave**: A concept reflects the wave-particle duality of matter. The theory was proposed by Louis de Broglie.
- **Rayleigh criterion**: The angular resolution of an optical system can be estimated from the diameter of the aperture and the wavelength of the light, which was first proposed by Lord Rayleigh.
- **probability density function**: Any function whose integral over a set gives the probability that a random variable has a value in that set.
- **Bell's theorem**: A no-go theorem famous for drawing an important line in the sand between quantum mechanics (QM) and the world as we know it classically. In its simplest form, Bell's theorem states: No physical theory of local hidden variables can

ever reproduce all of the predictions of quantum mechanics.

- **epistemological**: Of or pertaining to epistemology or theory of knowledge, as a field of study.

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8.2: Applications of Quantum Mechanics

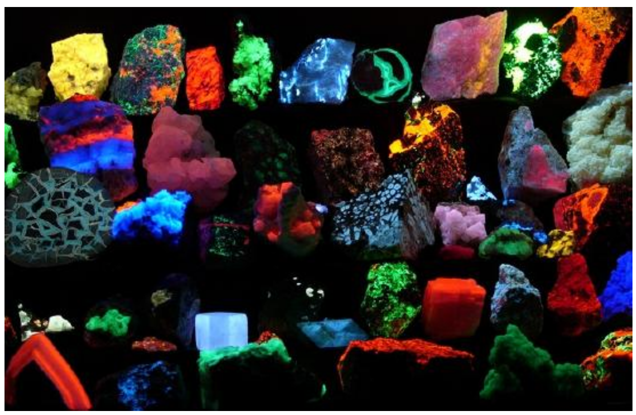
learning objectives

- Compare mechanisms of fluorescence and phosphorescence light emission

Fluorescence and Phosphorescence

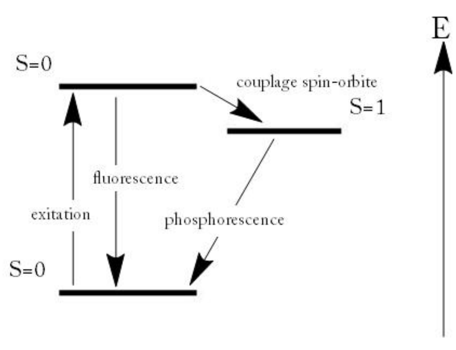
Fluorescence is the emission of light by a substance that has absorbed light or other electromagnetic radiation. It is a form of photoluminescence. In most cases, the emitted light has a longer wavelength, and therefore lower energy, than the absorbed radiation. However, when the absorbed electromagnetic radiation is intense, it is possible for one electron to absorb two photons; this two-photon absorption can lead to emission of radiation having a shorter wavelength than the absorbed radiation. The emitted radiation may also be of the same wavelength as the absorbed radiation, termed “resonance fluorescence”.

Fluorescence occurs when an orbital electron of a molecule or atom relaxes to its ground state by emitting a photon of light after being excited to a higher quantum state by some type of energy. The most striking examples of fluorescence occur when the absorbed radiation is in the ultraviolet region of the spectrum, and thus invisible to the human eye, and the emitted light is in the visible region.



Fluorescence: Fluorescent minerals emit visible light when exposed to ultraviolet light

Phosphorescence is a specific type of photoluminescence related to fluorescence. Unlike fluorescence, a phosphorescent material does not immediately re-emit the radiation it absorbs. Excitation of electrons to a higher state is accompanied with the change of a spin state. Once in a different spin state, electrons cannot relax into the ground state quickly because the re-emission involves quantum mechanically forbidden energy state transitions. As these transitions occur very slowly in certain materials, absorbed radiation may be re-emitted at a lower intensity for up to several hours after the original excitation.



Fluorescence and Phosphorescence: Energy scheme used to explain the difference between fluorescence and phosphorescence

Commonly seen examples of phosphorescent materials are the glow-in-the-dark toys, paint, and clock dials that glow for some time after being charged with a bright light such as in any normal reading or room light. Typically the glowing then slowly fades out within minutes (or up to a few hours) in a dark room.

Phosphorescence: Phosphorescent material glowing in the dark.

Lasers

A laser is a device that emits monochromatic light through a process of optical amplification based on the stimulated emission of photons.

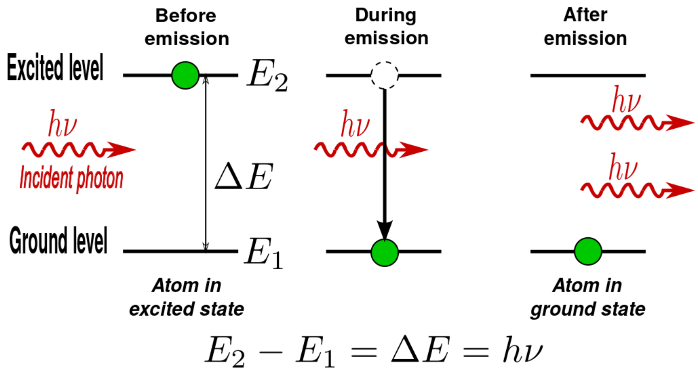
learning objectives

- Identify process that generates laser emission and the defining characteristics of laser light

A laser is a device that emits monochromatic light (electromagnetic radiation). It does so through a process of optical amplification based on the stimulated emission of photons. The term “laser” originated as an acronym for Light Amplification by Stimulated Emission of Radiation. Laser is distinct from other light sources for its high degree of spatial and temporal coherence, which means that laser outputs a narrow beam that maintains its temporal-phase relationship.

Principles of laser operation are largely based on quantum mechanics. (One exception would be free-electron lasers, whose operation can be explained solely by classical electrodynamics.) When an electron is excited from a lower-energy to a higher-energy level, it will not stay that way forever. An electron in an excited state may decay to an unoccupied lower-energy state according to a particular time constant characterizing that transition. When such an electron decays without external influence, it emits a photon; this process is called “spontaneous emission. ” The phase associated with the emitted photon is random. A material with many atoms in an excited state may thus result in radiation that is very monochromatic, but the individual photons would have no common phase relationship and would emanate in random directions. This is the mechanism of fluorescence and thermal emission.

However, an external photon at a frequency associated with the atomic transition can affect the quantum mechanical state of the atom. As the incident photon passes by, the rate of transitions of the excited atom can be significantly enhanced beyond that due to spontaneous emission. This “induced” decay process is called stimulated emission. In stimulated emission, the decaying atom produces an identical “copy” of the incoming photon. Therefore, after the atom decays, we have two identical outgoing photons. Since there was only one *incoming* photon, we amplified the intensity of light by a factor of 2!



Stimulated Photon Emission: In stimulated emission process, a photon (with a frequency equal to the atomic transition) encounters an excited atom, and a new photon identical to the incoming photon is produced. The result is an atom in the ground state with two outgoing photons.

Holography

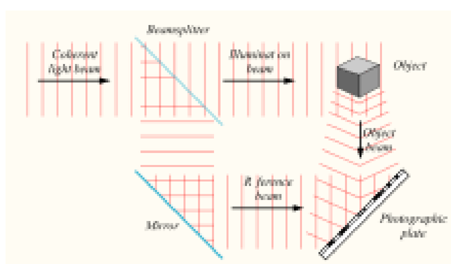
Holography is an optical technique which enables three-dimensional images to be made.

learning objectives

- Explain how holographic images are recorded and their properties

Holography is a technique which enables three-dimensional images to be made. It involves the use of a laser, interference, diffraction, light intensity recording and suitable illumination of the recording. The image changes as the position and orientation of the viewing system changes in exactly the same way as if the object were still present, thus making the image appear three-dimensional.

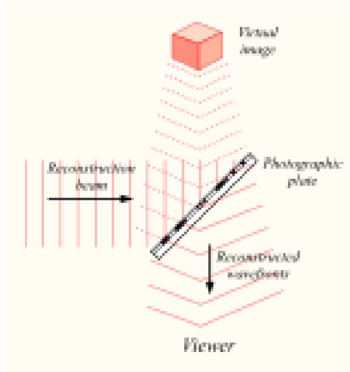
Laser: Holograms are recorded using a flash of light that illuminates a scene and then imprints on a recording medium, much in the way a photograph is recorded. In addition, however, part of the light beam must be shone directly onto the recording medium – this second light beam is known as the reference beam ([]). A hologram requires a laser as the sole light source. Laser is required as a light source to produce an interference pattern on the recording plate. To prevent external light from interfering, holograms are usually taken in darkness, or in low level light of a different color from the laser light used in making the hologram. Holography requires a specific exposure time, which can be controlled using a shutter, or by electronically timing the laser



Recording a hologram: Holograms are recorded using a flash of light that illuminates a scene and then imprints on a recording medium, much in the way a photograph is recorded. In addition, however, part of the light beam must be shone directly onto the recording medium – this second light beam is known as the reference beam.

Apparatus: A hologram can be made by shining part of the light beam directly onto the recording medium, and the other part onto the object in such a way that some of the scattered light falls onto the recording medium. A more flexible arrangement for recording a hologram requires the laser beam to be aimed through a series of elements that change it in different ways. The first element is a beam splitter that divides the beam into two identical beams, each aimed in different directions:

- One beam (known as the illumination or object beam) is spread using lenses and directed onto the scene using mirrors. Some of the light scattered (reflected) from the scene then falls onto the recording medium.
- The second beam (known as the reference beam) is also spread through the use of lenses, but is directed so that it doesn't come in contact with the scene, and instead travels directly onto the recording medium.



Reconstructing a hologram: An interference pattern can be considered an encoded version of a scene, requiring a particular key – the original light source – in order to view its contents. This missing key is provided later by shining a laser, identical to the one used to record the hologram, onto the developed film. When this beam illuminates the hologram, it is diffracted by the hologram's surface pattern. This produces a light field identical to the one originally produced by the scene and scattered onto the hologram

Several different materials can be used as the recording medium. One of the most common is a film very similar to photographic film (silver halide photographic emulsion), but with a much higher concentration of light-reactive grains, making it capable of the much higher resolution that holograms require. A layer of this recording medium (e.g. silver halide) is attached to a transparent substrate, which is commonly glass, but may also be plastic.

Process: When the two laser beams reach the recording medium, their light waves intersect and interfere with each other. It is this interference pattern that is imprinted on the recording medium. The pattern itself is seemingly random, as it represents the way in which the scene's light interfered with the original light source – but not the original light source itself. The interference pattern can be considered an encoded version of the scene, requiring a particular key – the original light source – in order to view its contents.

This missing key is provided later by shining a laser, identical to the one used to record the hologram, onto the developed film. When this beam illuminates the hologram, it is diffracted by the hologram's surface pattern. This produces a light field identical to the one originally produced by the scene and scattered onto the hologram. The image this effect produces in a person's retina is known as a virtual image.

The Periodic Table of Elements

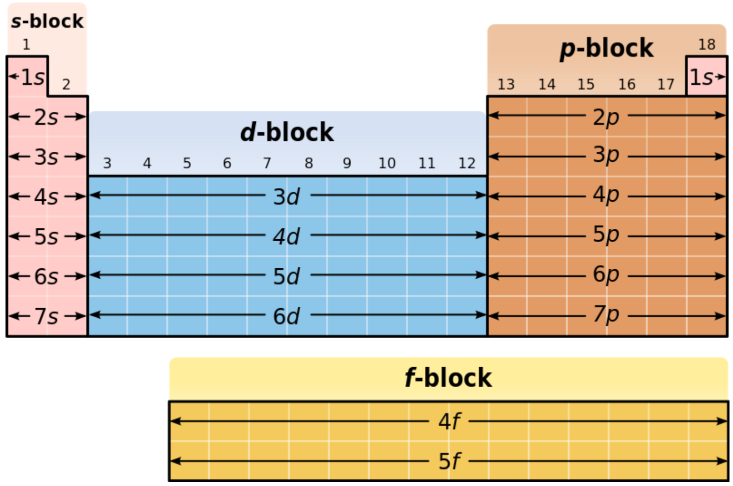
A periodic table is a tabular display of elements organized by their atomic numbers, electron configurations, and chemical properties.

learning objectives

- Explain how properties of elements vary within groups and across periods in the periodic table

The periodic table is a tabular display of the chemical elements. The elements are organized based on their atomic numbers, electron configurations, and recurring chemical properties.

In the periodic table, elements are presented in order of increasing atomic number (the number of protons). The rows of the table are called periods; the columns of the s- (columns 1-2 and He), d- (columns 3-12), and p-blocks (columns 13-18, except He) are called groups. (The terminology of s-, p-, and d- blocks originate from the valence atomic orbitals the element's electrons occupy.) Some groups have specific names, such as the halogens or the noble gases. Since, by definition, a periodic table incorporates recurring trends, any such table can be used to derive relationships between the properties of the elements and predict the properties of new, yet-to-be-discovered, or synthesized elements. As a result, the periodic table provides a useful framework for analyzing chemical behavior, and such tables are widely used in chemistry and other sciences.



Blocks in the Periodic Table: A diagram of the periodic table, highlighting the different blocks

History of the Periodic Table

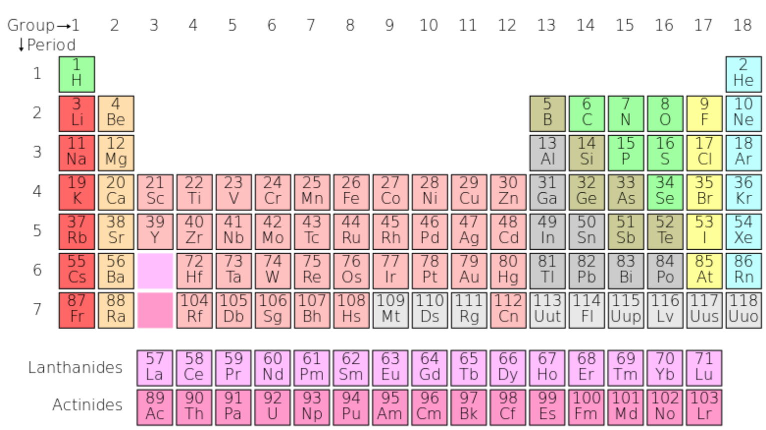
Although precursors exist, Dmitri Mendeleev is generally credited with the publication, in 1869, of the first widely recognized periodic table. Mendeleev designed the table in such a way that recurring ("periodic") trends in the properties of the elements could be shown. Using the trends he observed, he even left gaps for those elements that he thought were "missing. " He even predicted the properties that he thought the missing elements would have when they were discovered. Many of these elements were indeed later discovered, and Mendeleev's predictions were proved to be correct.

Groups

Agroup, or family, is a vertical column in the periodic table. Groups usually have more significant periodic trends than do periods and blocks, which are explained below. Modern quantum mechanical theories of atomic structure explain group trends by proposing that elements in the same group generally have the same electron configurations in their valence (or outermost, partially filled) shell. Consequently, elements in the same group tend to have shared chemistry and exhibit a clear trend in properties with increasing atomic number. However, in some parts of the periodic table, such as the d-block and the f-block, horizontal similarities can be as important as, or more pronounced than, vertical similarities.

Periods

A period is a horizontal row in the periodic table. Although groups generally have more significant periodic trends, there are regions where horizontal trends are more significant than vertical group trends, such as in the f-block, where the lanthanides and actinides form two substantial horizontal series of elements. Elements in the same period show trends in atomic radius, ionization energy, and electron affinity. Atomic radius usually decreases from left to right across a period. This occurs because each successive element has an added proton and electron, which causes the electron to be drawn closer to the nucleus, decreasing the radius.



The periodic table: Here is the complete periodic table with atomic numbers, groups, and periods. Each entry on the periodic table represents one element, and compounds are made up of several of these elements.

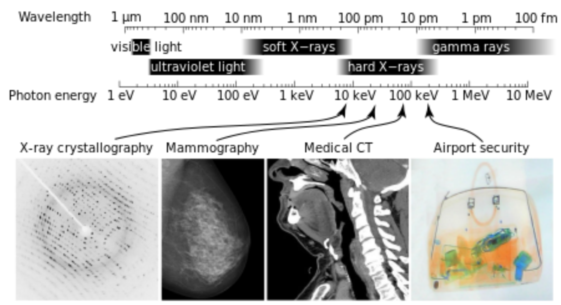
X-Rays

X-rays are a form of electromagnetic radiation and have wavelengths in the range of 0.01 to 10 nanometers.

learning objectives

- Describe the properties of X-rays and how can be generated

X-radiation (composed of x-rays) is a form of electromagnetic radiation. X-rays have wavelengths in the range of 0.01 to 10 nanometers, which corresponds to frequencies in the range of 30 petahertz to 30 exahertz ($3 \cdot 10^{16}$ Hz to $3 \cdot 10^{19}$ Hz) and energies in the of range 100 eV to 100 keV.



X-Ray Spectrum and Applications: X-rays are part of the electromagnetic spectrum, with wavelengths shorter than those of visible light. Different applications use different parts of the X-ray spectrum.

X-rays can be generated by an x-ray tube, a vacuum tube that uses high voltage to accelerate the electrons released by a hot cathode to a high velocity. The high-velocity electrons collide with a metal target, the anode, creating the x-rays. The maximum energy of the produced x-ray photon is limited by the energy of the incident electron, which is equal to the voltage on the tube times the electron charge, so an 80-kV tube cannot create x-rays with an energy greater than 80 keV. When the electrons hit the target, x-rays are created through two different atomic processes:

1. X-ray fluorescence, if the electron has enough energy that it can knock an orbital electron out of the inner electron shell of a metal atom. As a result, electrons from higher energy levels fill up the vacancy, and x-ray photons are emitted. This process produces an emission spectrum of x-rays at a few discrete frequencies, sometimes referred to as the spectral lines. The spectral lines generated depend on the target (anode) element used and therefore are called characteristic lines. Usually these are transitions from upper shells into the K shell (called K lines), or the L shell (called L lines), and so on.
2. *Bremsstrahlung*, literally meaning braking radiation. *Bremsstrahlung* is radiation given off by the electrons as they are scattered by the strong electric field near the high-Z (proton number) nuclei. These x-rays have a continuous spectrum. The intensity of the x-rays increases linearly with decreasing frequency, from zero at the energy of the incident electrons, the voltage on the x-ray tube.

Both of these x-ray production processes are inefficient, with a production efficiency of only about one percent. Therefore, to produce a usable flux of x-rays, most of the electric power consumed by the tube is released as heat waste. The x-ray tube must be designed to dissipate this excess heat.

A specialized source of x-rays that is becoming widely used in research is synchrotron radiation, which is generated by particle accelerators. Its unique features are x-ray outputs many orders of magnitude greater than those of x-ray tubes, wide x-ray spectra, excellent collimation, and linear polarization.

Quantum-Mechanical View of Atoms

Atom is a basic unit of matter that consists of a nucleus surrounded by negatively charged electron cloud, commonly called atomic orbitals.

learning objectives

- Identify major contributions to the understanding of atomic structure that were made by Niels Bohr, Erwin Schrödinger, and Werner Heisenberg

The atom is a basic unit of matter that consists of a nucleus surrounded by negatively charged electrons. The atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons. The electrons of an atom are bound to the nucleus by the electromagnetic (Coulomb) force. Atoms are minuscule objects with diameters of a few tenths of a nanometer and tiny masses proportional to the volume implied by these dimensions. Atoms in solid states (or, to be precise, their electron clouds) can be observed individually using special instruments such as the scanning tunneling microscope.

Hydrogen-1 (one proton + one electron) is the simplest form of atoms, and not surprisingly, our quantum mechanical understanding of atoms evolved with the understanding of this species. In 1913, physicist Niels Bohr suggested that the electrons were confined into clearly defined, quantized orbits, and could jump between these, but could not freely spiral inward or outward in intermediate states. An electron must absorb or emit specific amounts of energy to transition between these fixed orbits. Bohr's model successfully explained spectroscopic data of hydrogen very well, but it adopted a semiclassical approach where electron was still considered a (classical) particle.

Adopting Louis de Broglie's proposal of wave-particle duality, Erwin Schrödinger, in 1926, developed a mathematical model of the atom that described the electrons as three-dimensional waveforms rather than point particles. A consequence of using waveforms to describe particles is that it is mathematically impossible to obtain precise values for both the position and momentum of a particle at the same time; this became known as the uncertainty principle, formulated by Werner Heisenberg in 1926. Thereafter, the planetary model of the atom was discarded in favor of one that described atomic orbital zones around the nucleus where a given electron is most likely to be observed.

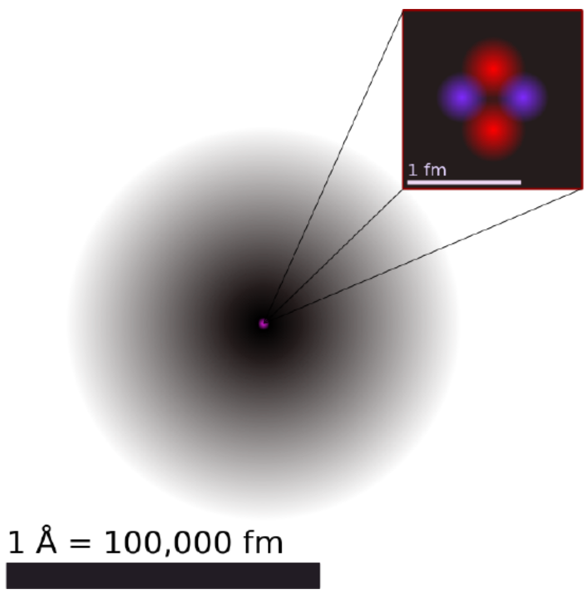


Illustration of the Helium Atom: This is an illustration of the helium atom, depicting the nucleus (pink) and the electron cloud distribution (black). The nucleus (upper right) in helium-4 is in reality spherically symmetric and closely resembles the electron cloud, although for more complicated nuclei this is not always the case. The black bar is one angstrom (10-10 m, or 100 pm).

Modern quantum mechanical view of hydrogen has evolved further after Schrödinger, by taking relativistic correction terms into account. Quantum electrodynamics (QED), a relativistic quantum field theory describing the interaction of electrically charged particles, has successfully predicted minuscule corrections in energy levels. One of the hydrogen's atomic transitions (n=2 to n=1, n: principal quantum number) has been measured to an extraordinary precision of 1 part in a hundred trillion. This kind of spectroscopic precision allows physicists to refine quantum theories of atoms, by accounting for minuscule discrepancies between experimental results and theories.

Key Points

- The emitted light usually has a longer wavelength, and therefore lower energy, than the absorbed radiation.
- Fluorescence occurs when an orbital electron of a molecule or atom relaxes to its ground state by emitting a photon of light after being excited to a higher quantum state by some type of energy.
- In a phosphorescence, excitation of electrons to a higher state is accompanied with the change of a spin state. Relaxation is a slow process since it involves energy state transitions "forbidden" in quantum mechanics.
- Principles of laser operation are largely based on quantum mechanics, most importantly on the process of the stimulated emission of photons.
- Spontaneous emission is a random decaying process. The phase associated with the emitted photon is also random.
- Atomic transition can be stimulated by the presence of an incoming photon at a frequency associated with the atomic transition. This process leads to optical amplification as an identical photon is emitted along with the incoming photon.
- When the two laser beams reach the recording medium, their light waves intersect and interfere with each other. It is this interference pattern that is imprinted on the recording medium.
- When a reconstruction beam illuminates the hologram, it is diffracted by the hologram's surface pattern. This produces a light field identical to the one originally produced by the scene and scattered onto the hologram.
- Holographic image changes as the position and orientation of the viewing system changes in exactly the same way as if the object were still present, thus making the image appear three-dimensional.
- A periodic table is a useful framework for analyzing chemical behavior. Such tables are widely used in chemistry and other sciences.
- A group, or family, is a vertical column in the periodic table. Groups usually have more significant periodic trends than do periods and blocks.
- A period is a horizontal row in the periodic table. Elements in the same period show trends in atomic radius, ionization energy, electron affinity, and electronegativity.
- X-rays can be generated by an x-ray tube, a vacuum tube, or a particle accelerator.
- X-ray fluorescence and Bremsstrahlung are processes through which x-rays are produced.
- Synchrotron radiation is generated by particle accelerators. Its unique features are x-ray outputs many orders of magnitude greater than those of x-ray tubes, wide x-ray spectra, excellent collimation, and linear polarization.
- Niels Bohr suggested that the electrons were confined into clearly defined, quantized orbits, and could jump between these, but could not freely spiral inward or outward in intermediate states.
- Erwin Schrödinger, in 1926, developed a mathematical model of the atom that described the electrons as three-dimensional waveforms rather than point particles.
- Modern quantum mechanical view of hydrogen has evolved further after Schrödinger, by taking relativistic correction terms into account. This is referred to a quantum electrodynamics (QED).

Key Terms

- **spin**: A quantum angular momentum associated with subatomic particles; it also creates a magnetic moment.
- **photon**: The quantum of light and other electromagnetic energy, regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime.
- **ground state**: the stationary state of lowest energy of a particle or system of particles
- **free-electron laser**: a laser that use a relativistic electron beam as the lasing medium, which moves freely through a magnetic structure
- **monochromatic**: Describes a beam of light with a single wavelength (i.e., of one specific color or frequency).
- **coherence**: an ideal property of waves that enables stationary (i.e., temporally and spatially constant) interference
- **interference**: An effect caused by the superposition of two systems of waves, such as a distortion on a broadcast signal due to atmospheric or other effects.
- **laser**: A device that produces a monochromatic, coherent beam of light.
- **silver halide**: The light-sensitive chemicals used in photographic film and pape
- **atomic orbital**: The quantum mechanical behavior of an electron in an atom describing the probability of the electron's particular position and energy.
- **electron affinity**: the amount of energy released when an electron is added to a neutral atom or molecule to form a negative ion
- **ionization energy**: the amount of energy required to remove an electron from an atom or molecule in the gas phase

- **photon**: The quantum of light and other electromagnetic energy, regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime.
- **particle accelerator**: A device that accelerates electrically charged particles to extremely high speeds, for the purpose of inducing high-energy reactions or producing high-energy radiation.
- **wave-particle duality**: A postulation that all particles exhibit both wave and particle properties. It is a central concept of quantum mechanics.
- **scanning tunneling microscope**: An instrument for imaging surfaces at the atomic level.
- **semiclassical approach**: A theory in which one part of a system is described quantum-mechanically whereas the other is treated classically.

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CHAPTER OVERVIEW

9: Atomic Physics

Topic hierarchy

9.1: Overview

learning objectives

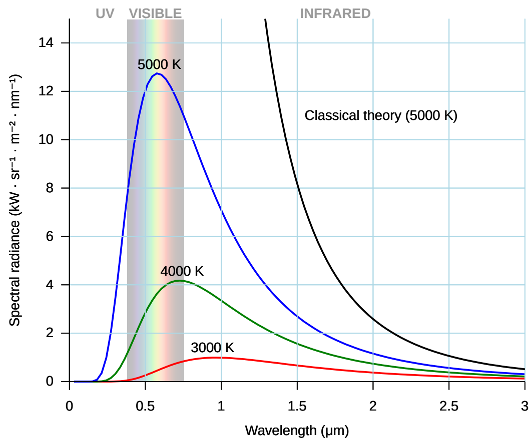
- Identify assumption made by Max Planck to describe the electromagnetic radiation emitted by a black body

A black body in thermal equilibrium (i.e. at a constant temperature) emits electromagnetic radiation called black body radiation. Black body radiation has a characteristic, continuous frequency spectrum that depends only on the body's temperature. Max Planck, in 1901, accurately described the radiation by assuming that electromagnetic radiation was emitted in discrete packets (or quanta). Planck's quantum hypothesis is a pioneering work, heralding advent of a new era of modern physics and quantum theory.

Explaining the properties of black-body radiation was a major challenge in theoretical physics during the late nineteenth century. Predictions based on classical theories failed to explain black body spectra observed experimentally, especially at shorter wavelength. The puzzle was solved in 1901 by Max Planck in the formalism now known as Planck's law of black-body radiation. Contrary to the common belief that electromagnetic radiation can take continuous values of energy, Planck introduced a radical concept that electromagnetic radiation was emitted in discrete packets (or quanta) of energy. Although Planck's derivation is beyond the scope of this section (it will be covered in Quantum Mechanics), Planck's law may be written:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{\frac{bc}{\lambda k_B T}} - 1} \tag{9.1.1}$$

where BB is the spectral radiance of the surface of the black body, TT is its absolute temperature, λλ is wavelength of the radiation, kBkB is the Boltzmann constant, hh is the Planck constant, and cc is the speed of light. This equation explains the black body spectra shown below. Planck's quantum hypothesis is one of the breakthroughs in the modern physics. It is not a surprise that he introduced Planck constant $h = 6.626 \times 10^{-34} J \cdot s$ for the first time in his derivation of the Planck's law.



Black body radiation spectrum: Typical spectrum from a black body at different temperatures (shown in blue, green and red curves). As the temperature decreases, the peak of the black-body radiation curve moves to lower intensities and longer wavelengths. Black line is a prediction of a classical theory for an object at 5,000K, showing catastropic discrepancy at shorter wavelengh.

Note that the spectral radiance depends on two variables, wavelength and temperature. The radiation has a specific spectrum and intensity that depends only on the temperature of the body. Despite its simplicity, Planck's law describes radiation properties of objects (e.g. our body, planets, stars) reasonably well.

Key Points

- A black body in thermal equilibrium emits electromagnetic radiation called black body radiation.
- The radiation has a specific spectrum and intensity that depends only on the temperature of the body.
- Max Planck, in 1901, accurately described the radiation by assuming that electromagnetic radiation was emitted in discrete packets (or quanta). Planck's quantum hypothesis is a pioneering work, heralding advent of a new era of modern physics and quantum theory.

Key Terms

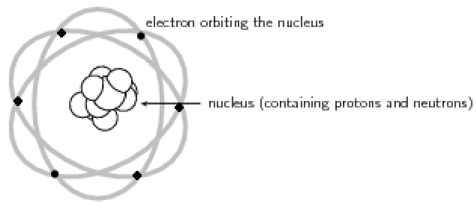
- **spectral radiance**: measures of the quantity of radiation that passes through or is emitted from a surface and falls within a given solid angle in a specified direction.
- **black body**: An idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. Although black body is a theoretical concept, you can find approximate realizations of black body in nature.
- **Planck constant**: a physical constant that is the quantum of action in quantum mechanics. It has a unit of angular momentum. The Planck constant was first described as the proportionality constant between the energy of a photon (unit of electromagnetic radiation) and the frequency of its associated electromagnetic wave in his derivation of the Planck's law

9.2: The Early Atom

learning objectives

- Discuss experiments that led to discovery of the electron and the nucleus

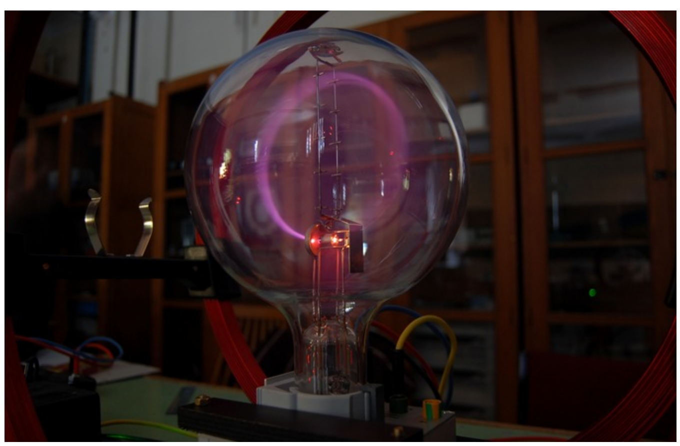
Though originally viewed as a particle that cannot be cut into smaller particles, modern scientific usage denotes the atom as composed of various subatomic particles. The constituent particles of an atom (each discovered independently) are: the electron, the proton and the neutron. (The hydrogen-1 atom, however, has no neutrons, and a positive hydrogen ion has no electrons.)



Classical Atomic Model: Atomic model before the advent of Quantum Mechanics.

Electron

The German physicist Johann Wilhelm Hittorf undertook the study of electrical conductivity in rarefied gases. In 1869, he discovered a glow emitted from the cathode that increased in size with decrease in gas pressure. In 1896, the British physicist J. J. Thomson performed experiments demonstrating that cathode rays were unique particles, rather than waves, atoms or molecules, as was believed earlier. Thomson made good estimates of both the charge ee and the mass mm, finding that cathode ray particles (which he called “corpuscles”) had perhaps one thousandth the mass of hydrogen, the least massive ion known. He showed that their charge to mass ratio (e/m) was independent of cathode material. (Fig 1 shows a beam of deflected electrons.)



Electron Beam: A beam of electrons deflected in a circle by a magnetic field.

Proton

In 1917 (in experiments reported in 1919), Rutherford proved that the hydrogen nucleus is present in other nuclei, a result usually described as the discovery of the proton. Earlier, Rutherford learned to create hydrogen nuclei as a type of radiation produced as a yield of the impact of alpha particles on hydrogen gas; these nuclei were recognized by their unique penetration signature in air and their appearance in scintillation detectors. These experiments began when Rutherford noticed that when alpha particles were shot into air (mostly nitrogen), his scintillation detectors displayed the signatures of typical hydrogen nuclei as a product. After experimentation Rutherford traced the reaction to the nitrogen in air, and found that the effect was larger when alphas were produced into pure nitrogen gas. Rutherford determined that the only possible source of this hydrogen was the nitrogen, and therefore nitrogen must contain hydrogen nuclei. One hydrogen nucleus was knocked off by the impact of the alpha particle, producing oxygen-17 in the process. This was the first reported nuclear reaction, $14\mathrm{N} + \alpha \rightarrow 17\mathrm{O} + \mathrm{p}$.

Neutron

In 1920, Ernest Rutherford conceived the possible existence of the neutron. In particular, Rutherford examined the disparity found between the atomic number of an atom and its atomic mass. His explanation for this was the existence of a neutrally charged particle within the atomic nucleus. He considered the neutron to be a neutral double consisting of an electron orbiting a proton. In 1932, James Chadwick showed uncharged particles in the radiation he used. These particles had a similar mass as protons, but did not have the same characteristics as protons. Chadwick followed some of the predictions of Rutherford, the first to work in this then unknown field.

Early Models of the Atom

Dalton believed that that matter is composed of discrete units called atoms — indivisible, ultimate particles of matter.

learning objectives

- Describe postulates of Dalton's atomic theory and the atomic theories of ancient Greek philosophers

The atom is a basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons. The atomic nucleus contains a mix of positively charged protons and electrically neutral neutrons (except in the case of hydrogen-1, which is the only stable nuclide with no neutrons). The electrons of an atom are bound to the nucleus by the electromagnetic force. We have a detailed (and accurate) model of the atom now, but it took a long time to come up with the correct answer.

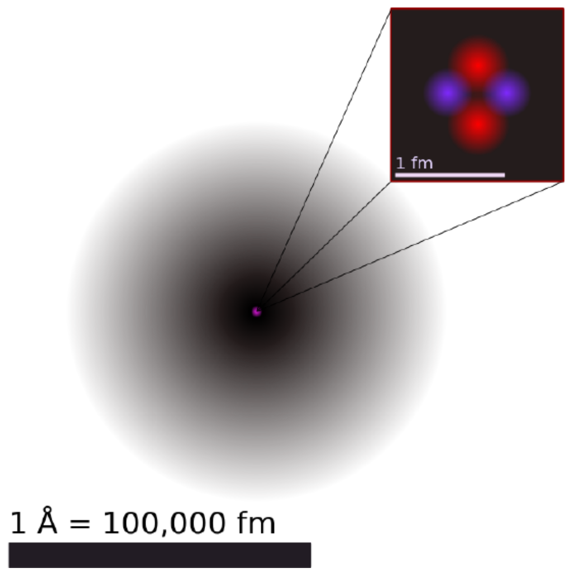


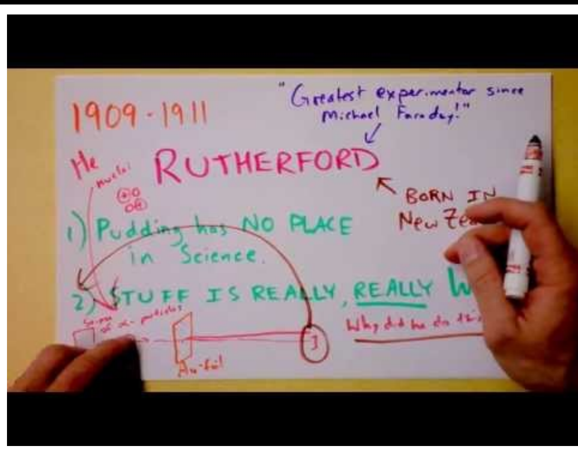
Illustration of the Helium Atom: This is an illustration of the helium atom, depicting the nucleus (pink) and the electron cloud distribution (black). The nucleus (upper right) in helium-4 is in reality spherically symmetric and closely resembles the electron cloud, although for more complicated nuclei this is not always the case. The black bar is one angstrom (10−1010−10 m, or 100 pm).

People have long speculated about the structure of matter and the existence of atoms. The earliest significant ideas to survive are from the ancient Greeks in the fifth century BC, especially from the philosophers Leucippus and Democritus. (There is some evidence that philosophers in both India and China made similar speculations at about the same time.) They considered the question of whether a substance can be divided without limit into ever smaller pieces. There are only a few possible answers to this question. One is that infinitesimally small subdivision is possible. Another is what Democritus in particular believed — that there is a smallest unit that cannot be further subdivided. Democritus called this the atom. We now know that atoms themselves can be subdivided, but their identity is destroyed in the process, so the Greeks were correct in a respect. The Greeks also felt that atoms were in constant motion, another correct notion.

The Greeks and others speculated about the properties of atoms, proposing that only a few types existed and that all matter was formed as various combinations of these types. The famous proposal that the basic elements were earth, air, fire, and water was brilliant but incorrect. The Greeks had identified the most common examples of the four states of matter (solid, gas, plasma, and liquid) rather than the basic chemical elements. More than 2000 years passed before observations could be made with equipment capable of revealing the true nature of atoms.

Over the centuries, discoveries were made regarding the properties of substances and their chemical reactions. Certain systematic features were recognized, but similarities between common and rare elements resulted in efforts to transmute them (lead into gold, in particular) for financial gain. Secrecy was commonplace. Alchemists discovered and rediscovered many facts but did not make them broadly available. As the Middle Ages ended, the practice of alchemy gradually faded, and the science of chemistry arose. It was no longer possible, nor considered desirable, to keep discoveries secret. Collective knowledge grew, and by the beginning of the 19th century, an important fact was well established: the masses of reactants in specific chemical reactions always have a particular mass ratio. This is very strong indirect evidence that there are basic units (atoms and molecules) that have these same mass ratios. English chemist John Dalton (1766-1844) did much of this work, with significant contributions by the Italian physicist Amedeo Avogadro (1776-1856). It was Avogadro who developed the idea of a fixed number of atoms and molecules in a mole. This special number is called Avogadro's number in his honor ($6.022 \cdot 1023$).

Dalton believed that matter is composed of discrete units called atoms, as opposed to the obsolete notion that matter could be divided into any arbitrarily small quantity. He also believed that atoms are the indivisible, ultimate particles of matter. However, this belief was overturned near the end of the 19th century by Thomson, with his discovery of electrons.



Intro to the History of Atomic Theory – Intro: Rutherford, Thomson, electrons, nuclei, and plums. I don't mean to be a bohr, but do you think pudding should have a role in serious scientific inquiry?

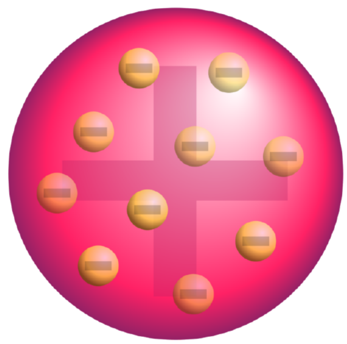
The Thomson Model

Thomson proposed that the atom is composed of electrons surrounded by a soup of positive charge to balance the electrons' negative charges.

learning objectives

- Describe model of an atom proposed by J. J. Thomson.

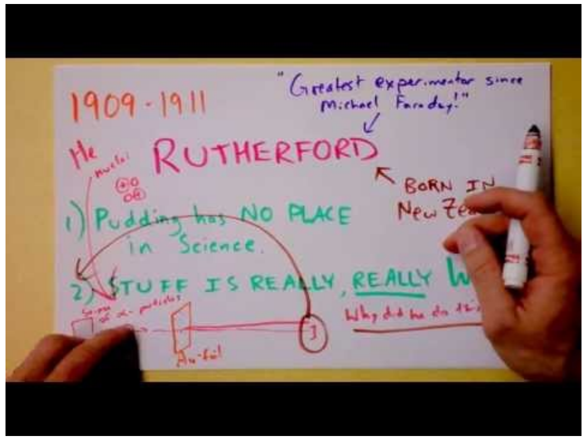
J. J. Thomson, who discovered the electron in 1897, proposed the plum pudding model of the atom in 1904 before the discovery of the atomic nucleus in order to include the electron in the atomic model. In Thomson's model, the atom is composed of electrons (which Thomson still called "corpuscles," though G. J. Stoney had proposed that atoms of electricity be called electrons in 1894) surrounded by a soup of positive charge to balance the electrons' negative charges, like negatively charged "plums" surrounded by positively charged "pudding". The electrons (as we know them today) were thought to be positioned throughout the atom in rotating rings. In this model the atom was also sometimes described to have a "cloud" of positive charge.



Plum pudding model of the atom: A schematic presentation of the plum pudding model of the atom; in Thomson's mathematical model the "corpuscles" (in modern language, electrons) were arranged non-randomly, in rotating rings.

With this model, Thomson abandoned his earlier "nebular atom" hypothesis, in which the atom was composed of immaterial vortices. Now, at least part of the atom was to be composed of Thomson's particulate negative corpuscles, although the rest of the positively charged part of the atom remained somewhat nebulous and ill-defined.

The 1904 Thomson model was disproved by the 1909 gold foil experiment performed by Hans Geiger and Ernest Marsden. This gold foil experiment was interpreted by Ernest Rutherford in 1911 to suggest that there is a very small nucleus of the atom that contains a very high positive charge (in the case of gold, enough to balance the collective negative charge of about 100 electrons). His conclusions led him to propose the Rutherford model of the atom.



Intro to the History of Atomic Theory – The Thomson Model: Rutherford, Thomson, electrons, nuclei, and plums. I don't mean to be a bohr, but do you think pudding should have a role in serious scientific inquiry?

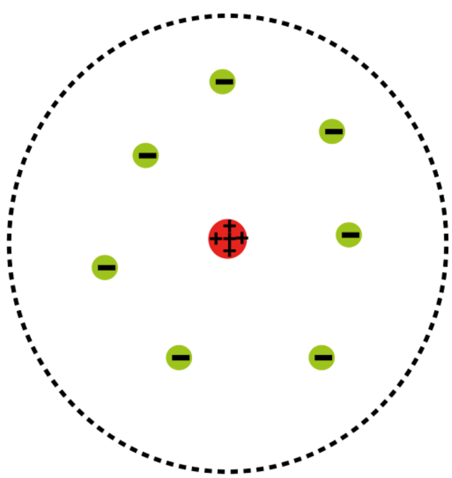
The Rutherford Model

Rutherford confirmed that the atom had a concentrated center of positive charge and relatively large mass.

learning objectives

- Describe gold foil experiment performed by Geiger and Marsden under directions of Rutherford and its implications for the model of the atom

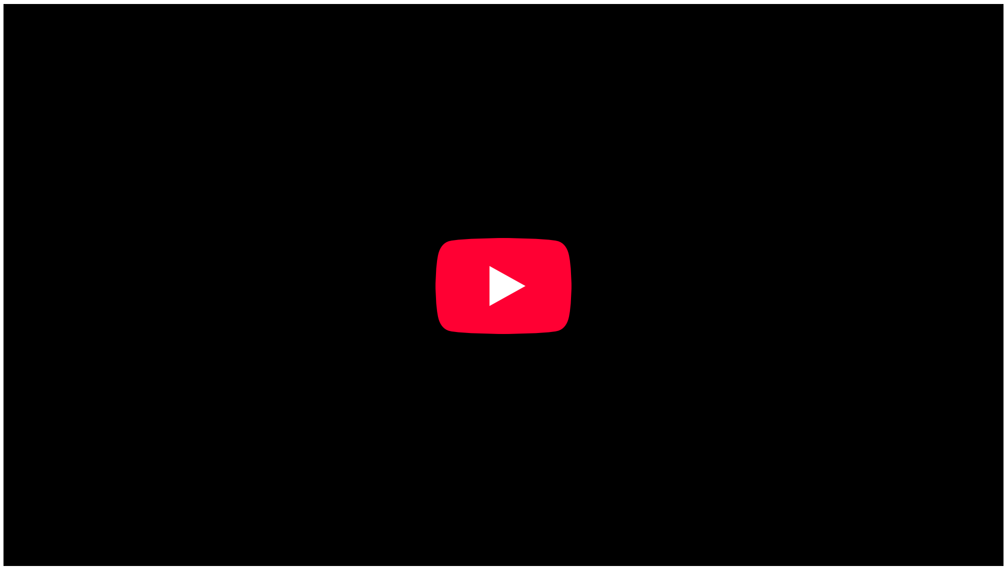
The Rutherford model is a model of the atom named after Ernest Rutherford. Rutherford directed the famous Geiger-Marsden experiment in 1909, which suggested, according to Rutherford's 1911 analysis, that J. J. Thomson's so-called "plum pudding model" of the atom was incorrect. Rutherford's new model for the atom, based on the experimental results, contained the new features of a relatively high central charge concentrated into a very small volume in comparison to the rest of the atom. This central volume also contained the bulk of the atom's mass. This region would later be named the "nucleus. "

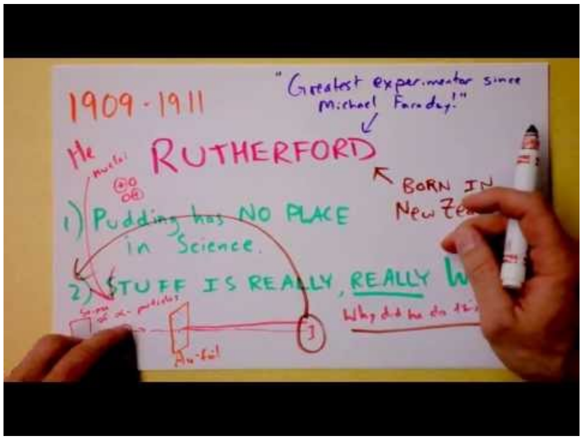


Atomic Planetary Model: Basic diagram of the atomic planetary model; electrons are in green, and the nucleus is in red

In 1911, Rutherford designed an experiment to further explore atomic structure using the alpha particles emitted by a radioactive element. Following his direction, Geiger and Marsden shot alpha particles with large kinetic energies toward a thin foil of gold. Measuring the pattern of scattered particles was expected to provide information about the distribution of charge within the atom. Under the prevailing plum pudding model, the alpha particles should all have been deflected by, at most, a few degrees. However, the actual results surprised Rutherford. Although many of the alpha particles did pass through as expected, many others were deflected at small angles while others were reflected back to the alpha source.

From purely energetic considerations of how far particles of known speed would be able to penetrate toward a central charge of 100 e, Rutherford was able to calculate that the radius of his gold central charge would need to be less than 3.4·10−143.4·10−14 meters. This was in a gold atom known to be about 10−1010−10 meters in radius; a very surprising finding, as it implied a strong central charge less than 1300013000th of the diameter of the atom.





Intro to the History of Atomic Theory – The Rutherford Model: Rutherford, Thomson, electrons, nuclei, and plums. I don't mean to be a bohr, but do you think pudding should have a role in serious scientific inquiry?

The Bohr Model of the Atom

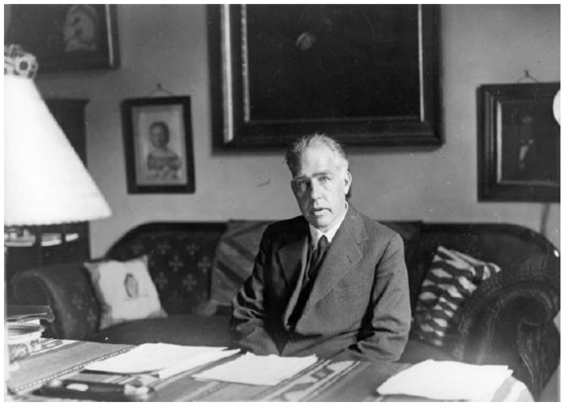
Bohr suggested that electrons in hydrogen could have certain classical motions *only when restricted by a quantum rule*.

learning objectives

- Describe model of atom proposed by Niels Bohr.

The Bohr Model of the Atom

The great Danish physicist Niels Bohr (1885–1962,) made immediate use of Rutherford's planetary model of the atom. Bohr became convinced of its validity and spent part of 1912 at Rutherford's laboratory. In 1913, after returning to Copenhagen, he began publishing his theory of the simplest atom, hydrogen, based on the planetary model of the atom.



Niels Bohr: Niels Bohr, Danish physicist, used the planetary model of the atom to explain the atomic spectrum and size of the hydrogen atom. His many contributions to the development of atomic physics and quantum mechanics; his personal influence on many students and colleagues; and his personal integrity, especially in the face of Nazi oppression, earned him a prominent place in history. (credit: Unknown Author, via Wikimedia Commons)

For decades, many questions had been asked about atomic characteristics. From their sizes to their spectra, much was known about atoms, but little had been explained in terms of the laws of physics. Bohr's theory explained the atomic spectrum of hydrogen, made him instantly famous, and established new and broadly applicable principles in quantum mechanics.

One big puzzle that the planetary-model of atom had was the following. The laws of classical mechanics predict that the electron should release electromagnetic radiation while orbiting a nucleus (according to Maxwell's equations, accelerating charge should emit electromagnetic radiation). Because the electron would lose energy, it would gradually spiral inwards, collapsing into the nucleus. This atom model is disastrous, because it predicts that all atoms are unstable. Also, as the electron spirals inward, the emission would gradually increase in frequency as the orbit got smaller and faster. This would produce a continuous smear, in frequency, of electromagnetic radiation. However, late 19th century experiments with electric discharges have shown that atoms will only emit light (that is, electromagnetic radiation) at certain discrete frequencies.

To overcome this difficulty, Niels Bohr proposed, in 1913, what is now called the Bohr model of the atom. He suggested that electrons could only have certain classical motions:

1. Electrons in atoms orbit the nucleus.
2. The electrons can only orbit stably, without radiating, in certain orbits (called by Bohr the "stationary orbits"): at a certain discrete set of distances from the nucleus. These orbits are associated with definite energies and are also called energy shells or energy levels. In these orbits, the electron's acceleration does not result in radiation and energy loss as required by classical electrodynamics.
3. Electrons can only gain and lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation with a frequency νν determined by the energy difference of the levels according to the Planck relation:

$$\Delta \mathrm{E}=\mathrm{E}_2-\mathrm{E}_1=\mathrm{h}\nu \tag{9.2.1}$$

where h is Planck's constant and ν is the frequency of the radiation.

Semiclassical Model

The significance of the Bohr model is that the laws of classical mechanics apply to the motion of the electron about the nucleus *only when restricted by a quantum rule*. Therefore, his atomic model is called a semiclassical model.

Basic Assumptions of the Bohr Model

Bohr explained hydrogen's spectrum successfully by adopting a quantization condition and by introducing the Planck constant in his model.

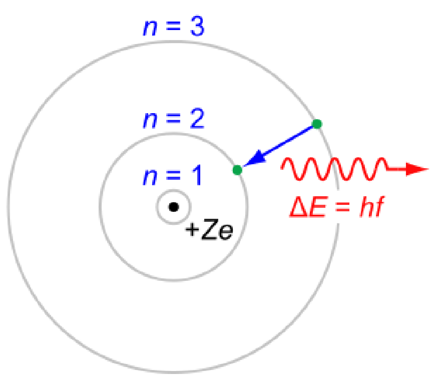
learning objectives

- Describe basic assumptions that were applied by Niels Bohr to the planetary model of an atom

In previous modules, we have seen puzzles from classical atomic theories (e.g., the Rutherford model). Most importantly, classical electrodynamics predicts that an atom described by a (classical) planetary model would be unstable. To explain the puzzle, Bohr proposed what is now called the Bohr model of the atom in 1913. He suggested that electrons could only have certain classical motions:

1. Electrons in atoms orbit the nucleus.
2. The electrons can only orbit stably, without radiating, in certain orbits (called by Bohr the "stationary orbits") at a certain discrete set of distances from the nucleus. These orbits are associated with definite energies and are also called energy shells or energy levels. In these orbits, the electron's acceleration does not result in radiation and energy loss as required by classical electrodynamics.
3. Electrons can only gain and lose energy by jumping from one allowed orbit to another, absorbing or emitting electromagnetic radiation with a frequency νν determined by the energy difference of the levels according to the Planck relation: $\Delta \mathrm{E}=\mathrm{E}_2-\mathrm{E}_1=\mathrm{h}\nu$, where h is the Planck constant. In addition, Bohr also assumed that the angular momentum L is restricted to be an integer multiple of a fixed unit: $\mathrm{L}=\mathrm{n}\frac{\mathrm{h}}{2\pi}=\mathrm{n}\hbar$, where $\mathrm{n}=1,2,3,\ldots$ is called the principal quantum number, and $\hbar=\frac{h}{2\pi}$.

We have seen that Planck adopted a new condition of energy quantization to explain the black body radiation, where he introduced the Planck constant hh for the first time. Soon after, Einstein resorted to this new concept of energy quantization and used the Planck constant again to explain the photoelectric effects, in which he assumed that electromagnetic radiation interact with matter as particles (later named "photons"). Here, Bohr explained the atomic hydrogen spectrum successfully for the first time by adopting a quantization condition and by introducing the Planck constant in his atomic model. Over the period of radical development in the early 20th century, physicists began to realize that it was essential to introduce the notion of "quantization" to explain microscopic worlds.



Rutherford-Bohr model: The Rutherford–Bohr model of the hydrogen atom ($\mathrm{Z}=1$) or a hydrogen-like ion ($\mathrm{Z}>1$), where the negatively charged electron confined to an atomic shell encircles a small, positively charged atomic nucleus, and where an electron jump between orbits is accompanied by an emitted or absorbed amount of electromagnetic energy (hνhν). The orbits in which the electron may travel are shown as gray circles; their radius increases as n^2, where n is the principal quantum number. The $3\rightarrow 2$ transition depicted here produces the first line of the Balmer series, and for hydrogen ($\mathrm{Z}=1$) it results in a photon of wavelength 656 nm (red light).

Bohr Orbits

According to Bohr, electrons can only orbit stably, in certain orbits, at a certain discrete set of distances from the nucleus.

learning objectives

- Explain relationship between the "Bohr orbits" and the quantization effect

Danish Physicist Neils Bohr was clever enough to discover a method of calculating the electron orbital energies in hydrogen. As we've seen in the previous module "The Bohr Model of Atom," Bohr assumed that the electrons can only orbit stably, without radiating, in certain orbits (named by Bohr as "stationary orbits"), at a certain discrete set of distances from the nucleus. These "Bohr orbits" have a very important feature of quantization as shown in the following. This was an important first step that has been improved upon, but it is well worth repeating here, as it correctly describes many characteristics of hydrogen. Assuming circular orbits, Bohr proposed that the angular momentum LL of an electron in its orbit is quantized, that is, has only specific, discrete values. The value for LL is given by the formula:

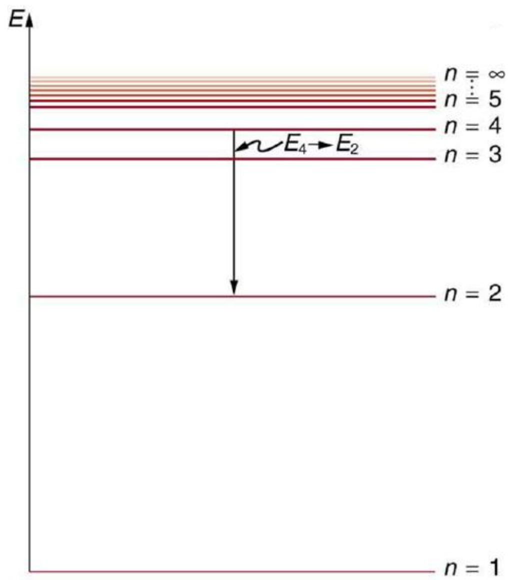
$$L = m_e v r_n = n\frac{h}{2\pi} = n\hbar \tag{9.2.2}$$

where LL is the angular momentum, meme is the electron's mass, rnrn is the radius of the nn-th orbit, and hh is Planck's constant. Note that angular momentum is $L = I\omega$. For a small object at a radius $r, I = mr^2$ and $\omega = \frac{v}{r}$, so that:

$$L = (mr^2)\left(\frac{v}{r}\right) = mvr \tag{9.2.3}$$

Quantization says that this value of mvrmvr can only have discrete values. At the time, Bohr himself did not know why angular momentum should be quantized, but using this assumption he was able to calculate the energies in the hydrogen spectrum, something no one else had done at the time.

Below is an energy-level diagram, which is a convenient way to display energy states—the allowed energy levels of the electron (as relative to our discussion). Energy is plotted vertically with the lowest or ground state at the bottom and with excited states above. Given the energies of the lines in an atomic spectrum, it is possible (although sometimes very difficult) to determine the energy levels of an atom. Energy-level diagrams are used for many systems, including molecules and nuclei. A theory of the atom or any other system must predict its energies based on the physics of the system.



Energy-Level Diagram Plot: An energy-level diagram plots energy vertically and is useful in visualizing the energy states of a system and the transitions between them. This diagram is for the hydrogen-atom electrons, showing a transition between two orbits having energies E_4 and E_2.

Energy of a Bohr Orbit

Based on his assumptions, Bohr derived several important properties of the hydrogen atom from the classical physics.

learning objectives

- Apply proper equation to calculate energy levels and the energy of an emitted photon for a hydrogen-like atom

From Bohr's assumptions, we will now derive a number of important properties of the hydrogen atom from the classical physics. We start by noting the centripetal force causing the electron to follow a circular path is supplied by the Coulomb force. To be more general, we note that this analysis is valid for any single-electron atom. So, if a nucleus has Z protons ($Z=1$ for hydrogen, $Z=2$ for helium, etc.) and only one electron, that atom is called a hydrogen-like atom.

The spectra of hydrogen-like ions are similar to hydrogen, but shifted to higher energy by the greater attractive force between the electron and nucleus. The magnitude of the centripetal force is $\frac{m_e v^2}{r_n}$, while the Coulomb force is $\frac{Zk_e e^2}{r^2}$. The tacit assumption here is that the nucleus is more massive than the stationary electron, and the electron orbits about it. This is consistent with the planetary model of the atom. Equating these:

$$\frac{m_e v^2}{r} = \frac{Zk_e e^2}{r^2} \tag{9.2.4}$$

This equation determines the electron's speed at any radius:

$$v = \frac{\sqrt{Zk_e e^2}}{m_e r} \tag{9.2.5}$$

It also determines the electron's total energy at any radius:

$$E = \frac{1}{2} m_e v^2 - \frac{Zk_e e^2}{r} = -\frac{Zk_e e^2}{2r} \tag{9.2.6}$$

The total energy is negative and inversely proportional to r. This means that it takes energy to pull the orbiting electron away from the proton. For infinite values of r, the energy is zero, corresponding to a motionless electron infinitely far from the proton.

Now, here comes the Quantum rule: As we saw in the previous module, the angular momentum $L=m_e r v$ is an integer multiple of $\hbar$:

$$m_e v r = n\hbar \tag{9.2.7}$$

Substituting the expression in the equation for speed above gives an equation for r in terms of n:

$$\sqrt{Zk_e e^2 m_e r} = n\hbar \tag{9.2.8}$$

The allowed orbit radius at any n is then:

$$r_n = \frac{n^2 \hbar^2}{Zk_e e^2 m_e} \tag{9.2.9}$$

The smallest possible value of r in the hydrogen atom is called the Bohr radius and is equal to 0.053 nm. The energy of the n-th level for any atom is determined by the radius and quantum number:

$$E = -\frac{Zk_e e^2}{2r_n} = -\frac{Z^2 \left(k_e e^2\right)^2 m_e}{2\hbar^2 n^2} \approx \frac{-13.6 Z^2}{n^2} \mathrm{eV} \tag{9.2.10}$$

Using this equation, the energy of a photon emitted by a hydrogen atom is given by the difference of two hydrogen energy levels:

$$E = E_i - E_f = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \tag{9.2.11}$$

Which is the Rydberg formula describing all the hydrogen spectrum and R is the Rydberg constant. Bohr's model predicted experimental hydrogen spectrum extremely well.

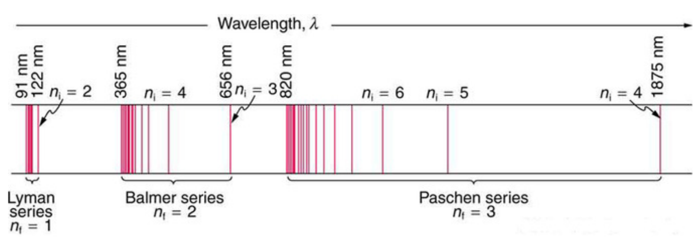


Fig 1: A schematic of the hydrogen spectrum shows several series named for those who contributed most to their determination. Part of the Balmer series is in the visible spectrum, while the Lyman series is entirely in the UV, and the Paschen series and others are in the IR. Values of nf and ni are shown for some of the lines.

Hydrogen Spectra

The observed hydrogen-spectrum wavelengths can be calculated using the following formula: $\frac{1}{\lambda} = \mathrm{R}\left(\frac{1}{\mathrm{n}_\mathrm{f}^2} - \frac{1}{\mathrm{n}_\mathrm{i}^2}\right)$.

learning objectives

- Explain difference between Lyman, Balmer, and Paschen series

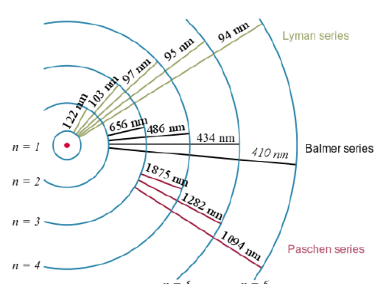
For decades, many questions had been asked about atomic characteristics. From their sizes to their spectra, much was known about atoms, but little had been explained in terms of the laws of physics. Atomic and molecular emission and absorption spectra have been known for over a century to be discrete (or quantized). Maxwell and others had realized that there must be a connection between the spectrum of an atom and its structure, something like the resonant frequencies of musical instruments. But, despite years of efforts by many great minds, no one had a workable theory. (It was a running joke that any theory of atomic and molecular spectra could be destroyed by throwing a book of data at it, so complex were the spectra.) Following Einstein's proposal of photons with quantized energies directly proportional to their wavelengths, it became even more evident that electrons in atoms can exist only in discrete orbits.

In some cases, it had been possible to devise formulas that described the emission spectra. As you might expect, the simplest atom —hydrogen, with its single electron—has a relatively simple spectrum. The hydrogen spectrum had been observed in the infrared (IR), visible, and ultraviolet (UV), and several series of spectral lines had been observed. The observed hydrogen-spectrum wavelengths can be calculated using the following formula:

$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \tag{9.2.12}$$

where λ is the wavelength of the emitted EM radiation and R is the Rydberg constant, determined by the experiment to be $\mathrm{R} = 1.097 \cdot 107\ \mathrm{m}^{-1}$, and $\mathrm{n_f}, \mathrm{n_i}$ are positive integers associated with a specific series.

These series are named after early researchers who studied them in particular depth. For the Lyman series, $\mathrm{n_f} = 1$ for the Balmer series, $\mathrm{n_f} = 2$; for the Paschen series, $\mathrm{n_f} = 3$; and so on. The Lyman series is entirely in the UV, while part of the Balmer series is visible with the remainder UV. The Paschen series and all the rest are entirely IR. There are apparently an unlimited number of series, although they lie progressively farther into the infrared and become difficult to observe as nfnfincreases. The constant nini is a positive integer, but it must be greater than $\mathrm{n_f}$. Thus, for the Balmer series, $\mathrm{n_f} = 2$ and$\mathrm{n_i} = 3, 4, 5, 6 \ldots$. Note that nini can approach infinity.



Electron transitions and their resulting wavelengths for hydrogen.: Energy levels are not to scale.

While the formula in the wavelengths equation was just a recipe designed to fit data and was not based on physical principles, it did imply a deeper meaning. Balmer first devised the formula for his series alone, and it was later found to describe all the other series by using different values of nfnf. Bohr was the first to comprehend the deeper meaning. Again, we see the interplay between experiment and theory in physics. Experimentally, the spectra were well established, an equation was found to fit the experimental data, but the theoretical foundation was missing.

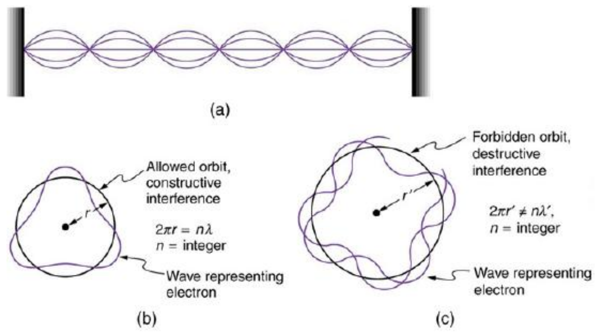
de Broglie and the Bohr Model

By assuming that the electron is described by a wave and a whole number of wavelengths must fit, we derive Bohr's quantization assumption.

learning objectives

- Describe reinterpretation of Bohr's condition by de Broglie

Bohr's condition, that the angular momentum is an integer multiple of $\hbar\hbar$, was later reinterpreted in 1924 by de Broglie as a standing wave condition. The wave-like properties of matter were subsequently confirmed by observations of electron interference when scattered from crystals. Electrons can exist only in locations where they interfere constructively. How does this affect electrons in atomic orbits? When an electron is bound to an atom, its wavelength must fit into a small space, something like a standing wave on a string.



Waves on a String: (a) Waves on a string have a wavelength related to the length of the string, allowing them to interfere constructively. (b) If we imagine the string bent into a closed circle, we get a rough idea of how electrons in circular orbits can interfere constructively. (c) If the wavelength does not fit into the circumference, the electron interferes destructively; it cannot exist in such an orbit.

Allowed orbits are those in which an electron constructively interferes with itself. Not all orbits produce constructive interference and thus only certain orbits are allowed (i.e., the orbits are quantized). By assuming that the electron is described by a wave and a whole number of wavelengths must fit along the circumference of the electron's orbit, we have the equation:

$$\mathrm{n}\lambda = 2\pi \mathrm{r} \tag{9.2.13}$$

Substituting de Broglie's wavelength of hphp reproduces Bohr's rule. Since λ=h/mevλ=h/mev, we now have:

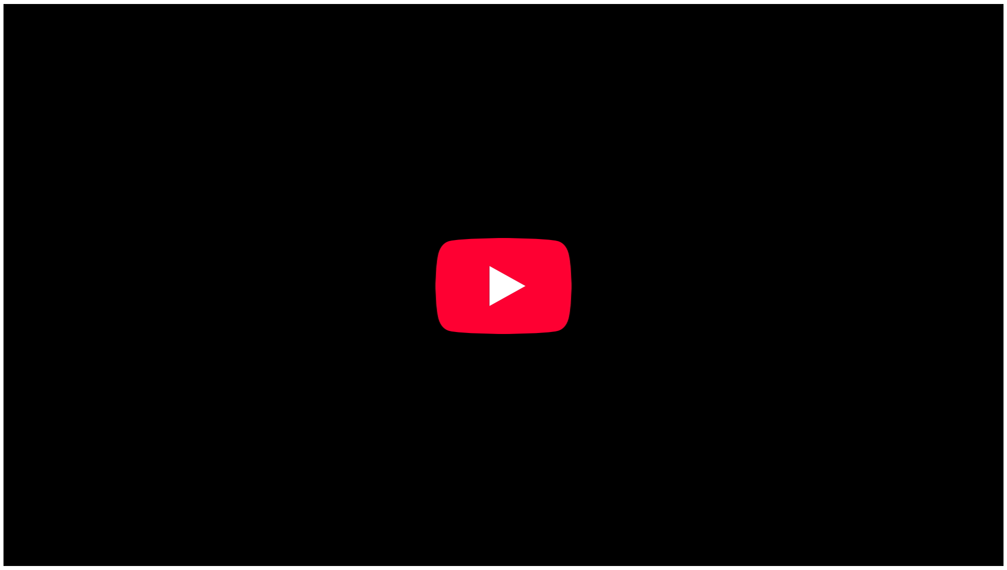
$$\frac{\mathrm{nh}}{\mathrm{m_{ev}}} = 2\pi \mathrm{r_n} \tag{9.2.14}$$

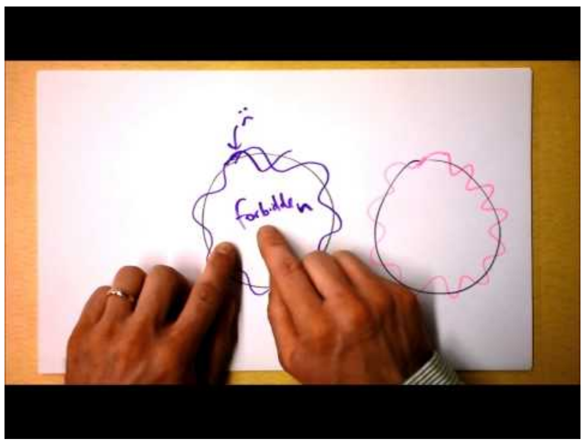
Rearranging terms, and noting that L=mvrL=mvr for a circular orbit, we obtain the quantization of angular momentum as the condition for allowed orbits:

$$\mathrm{L} = \mathrm{m_e v r_n} = \mathrm{n}\frac{\mathrm{h}}{2\pi}, (\mathrm{n} = 1, 2, 3\ldots) \tag{9.2.15}$$

As previously stated, Bohr was forced to hypothesize this rule for allowed orbits. We now realize this as the condition for constructive interference of an electron in a circular orbit.

Accordingly, a new kind of mechanics, quantum mechanics, was proposed in 1925. Bohr's model of electrons traveling in quantized orbits was extended into a more accurate model of electron motion. The new theory was proposed by Werner Heisenberg. By different reasoning, another form of the same theory, wave mechanics, was discovered independently by Austrian physicist Erwin Schrödinger. Schrödinger employed de Broglie's matter waves, but instead sought wave solutions of a three-dimensional wave equation. This described electrons that were constrained to move about the nucleus of a hydrogen-like atom by being trapped by the potential of the positive nuclear charge.





de Broglie’s Matter Waves Justify Bohr’s Magic Electron Orbital Radii: I include a summary of the hydrogen atom’s electronic structure and explain how an electron can interfere with itself in an orbit just like it can in a double-slit experiment.

X-Rays and the Compton Effect

Compton explained the X-ray frequency shift during the X-ray/electron scattering by attributing particle-like momentum to “photons”.

learning objectives

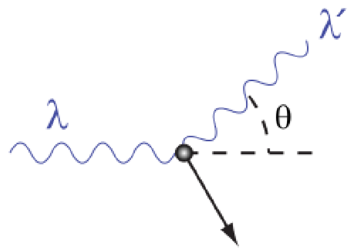
- Describe Compton effects between electrons and x-ray photons

By the early 20th century, research into the interaction of X-rays with matter was well underway. It was observed that when X-rays of a known wavelength interact with atoms, the X-rays are scattered through an angle $\theta\theta$ and emerge at a different wavelength related to $\theta\theta$. Although classical electromagnetism predicted that the wavelength of scattered rays should be equal to the initial wavelength, multiple experiments had found that the wavelength of the scattered rays was longer (corresponding to lower energy) than the initial wavelength.

In 1923, Compton published a paper in the Physical Review which explained the X-ray shift by attributing particle-like momentum to “photons,” which Einstein had invoked in his Nobel prize winning explanation of the photoelectric effect. First postulated by Planck, these “particles” conceptualized “quantized” elements of light as containing a specific amount of energy depending only on the frequency of the light. In his paper, Compton derived the mathematical relationship between the shift in wavelength and the scattering angle of the X-rays by assuming that each scattered X-ray photon interacted with only one electron. His paper concludes by reporting on experiments which verified his derived relation:

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta) \tag{9.2.16}$$

where λ\lambda is the initial wavelength, λ′\lambda’ is the wavelength after scattering, h is the Planck constant, m_e is the Electron rest mass, c is the speed of light, and θ\theta is the scattering angle. The quantity $\frac{h}{m_e c}$ is known as the Compton wavelength of the electron; it is equal to $2.43 \cdot 10^{-12}$ m. The wavelength shift $\lambda' - \lambda$ is at least zero (for $\theta = 0^\circ$) and at most twice the Compton wavelength of the electron (for $\theta = 0^\circ$). (The derivation of Compton’s formula is a bit lengthy and will not be covered here.)



A Photon Colliding with a Target at Rest: A photon of wavelength λλ comes in from the left, collides with a target at rest, and a new photon of wavelength λ‘λ‘ emerges at an angle θθ.

Because the mass-energy and momentum of a system must both be conserved, it is not generally possible for the electron simply to move in the direction of the incident photon. The interaction between electrons and high energy photons (comparable to the rest energy of the electron, 511 keV) results in the electron being given part of the energy (making it recoil), and a photon containing the remaining energy being emitted in a different direction from the original, so that the overall momentum of the system is conserved. If the scattered photon still has enough energy left, the Compton scattering process may be repeated. In this scenario, the electron is treated as free or loosely bound. Photons with an energy of this order of magnitude are in the x-ray range of the electromagnetic radiation spectrum. Therefore, you can say that Compton effects (with electrons) occur with x-ray photons.

If the photon is of lower energy, but still has sufficient energy (in general a few eV to a few keV, corresponding to visible light through soft X-rays), it can eject an electron from its host atom entirely (a process known as the photoelectric effect), instead of undergoing Compton scattering. Higher energy photons (1.022 MeV and above, in the gamma ray range) may be able to bombard the nucleus and cause an electron and a positron to be formed, a process called pair production.

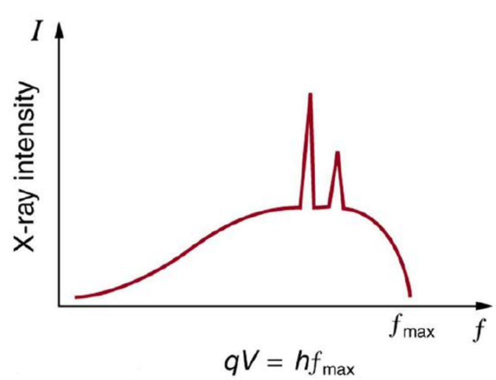
X-Ray Spectra: Origins, Diffraction by Crystals, and Importance

X-ray shows its wave nature when radiated upon atomic/molecular structures and can be used to study them.

learning objectives

- Describe interactions between X-rays and atoms

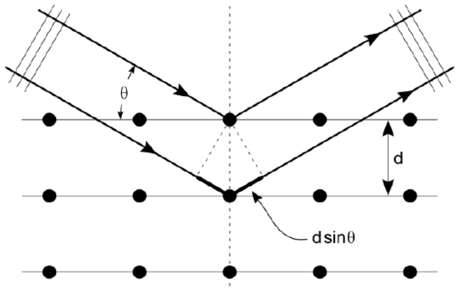
In a previous Atom on X-rays, we have seen that there are two processes by which x-rays are produced in the anode of an x-ray tube. In one process, the deceleration of electrons produces x-rays, and these x-rays are called *Bremsstrahlung*, or braking radiation. The second process is atomic in nature and produces characteristic x-rays, so called because they are characteristic of the anode material. The x-ray spectrum in is typical of what is produced by an x-ray tube, showing a broad curve of Bremsstrahlung radiation with characteristic x-ray peaks on it.



X-Ray Spectrum: X-ray spectrum obtained when energetic electrons strike a material, such as in the anode of a CRT. The smooth part of the spectrum is bremsstrahlung radiation, while the peaks are characteristic of the anode material. A different anode material would have characteristic x-ray peaks at different frequencies.

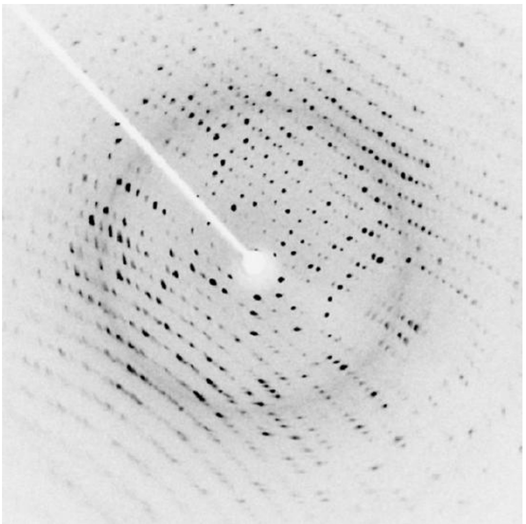
Since x-ray photons are very energetic, they have relatively short wavelengths. For example, the 54.4-keV Kα x-ray, for example, has a wavelength $\lambda=\frac{\mathrm{hc}}{\mathrm{E}}=0.0228$ nm. Thus, typical x-ray photons act like rays when they encounter macroscopic objects, like teeth, and produce sharp shadows. However, since atoms and atomic structures have a typical size on the order of 0.1 nm, x-ray shows its wave nature with them. The process is called x-ray diffraction because it involves the diffraction and interference of x-rays to produce patterns that can be analyzed for information about the structures that scattered the x-rays.

Shown below, Bragg's Law gives the angles for coherent and incoherent scattering of light from a crystal lattice, which happens during x-ray diffraction. When x-ray are incident on an atom, they make the electronic cloud move as an electromagnetic wave. The movement of these charges re-radiate waves with the same frequency. This is called Rayleigh Scattering, which you should remember from a previous atom. A similar thing happens when neutron waves from the nuclei scatter from interaction with an unpaired electron. These re-emitted wave fields interfere with each other either constructively or destructively, and produce a diffraction pattern that is captured by a sensor or film. This is called the Braggs diffraction, and is the basis for x-ray diffraction.



X-Ray Diffraction: Bragg's Law of diffraction: illustration of how x-rays interact with crystal lattice.

Perhaps the most famous example of x-ray diffraction is the discovery of the double-helix structure of DNA in 1953. Using x-ray diffraction data, researchers were able to discern the structure of DNA shows a diffraction pattern produced by the scattering of x-rays from a crystal of protein. This process is known as x-ray crystallography because of the information it can yield about crystal structure. Not only do x-rays confirm the size and shape of atoms, they also give information on the atomic arrangements in materials. For example, current research in high-temperature superconductors involves complex materials whose lattice arrangements are crucial to obtaining a superconducting material. These can be studied using x-ray crystallography.



X-Ray Diffraction: X-ray diffraction from the crystal of a protein, hen egg lysozyme, produced this interference pattern. Analysis of the pattern yields information about the structure of the protein.

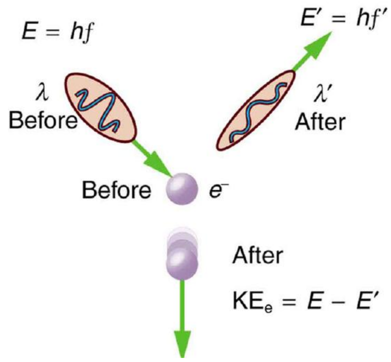
The Compton Effect

The Compton Effect is the phenomenon of the decrease in energy of photon when scattered by a free charged particle.

learning objectives

- Explain why Compton scattering is an inelastic scattering.

Compton scattering is an inelastic scattering of a photon by a free charged particle (usually an electron). It results in a decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma ray photon), called the Compton Effect. Part of the energy of the photon is transferred to the scattering electron. Inverse Compton scattering also exists, and happens when a charged particle transfers part of its energy to a photon.



Scattering in the Compton Effect: The Compton Effect is the name given to the scattering of a photon by an electron. Energy and momentum are conserved, resulting in a reduction of both for the scattered photon. Studying this effect, Compton verified that photons have momentum.

Compton scattering is an example of inelastic scattering because the wavelength of the scattered light is different from the incident radiation. Still, the origin of the effect can be considered as an elastic collision between a photon and an electron. The amount of change in the wavelength is called the Compton shift. Although nuclear Compton scattering exists, Compton scattering usually refers to the interaction involving only the electrons of an atom.

The Compton effect is important because it demonstrates that light cannot be explained purely as a wave phenomenon. Thomson scattering, the classical theory of an electromagnetic wave scattered by charged particles, cannot explain low intensity shifts in wavelength: classically, light of sufficient intensity for the electric field to accelerate a charged particle to a relativistic speed will cause radiation-pressure recoil and an associated Doppler shift of the scattered light. However, the effect will become arbitrarily small at sufficiently low light intensities regardless of wavelength. Light must behave as if it consists of particles to explain the low-intensity Compton scattering. Compton's experiment convinced physicists that light can behave as a stream of particle-like objects (quanta) whose energy is proportional to the frequency.

Key Points

- The British physicist J. J. Thomson performed experiments studying cathode rays and discovered that they were unique particles, later named electrons.
- Rutherford proved that the hydrogen nucleus is present in other nuclei.
- In 1932, James Chadwick showed that there were uncharged particles in the radiation he was using. These particles, later called neutrons, had a similar mass of the protons but did not have the same characteristics as protons.
- The atom is a basic unit of matter that consists of a dense central nucleus surrounded by a cloud of negatively charged electrons.
- Scattered knowledge discovered by alchemists over the Middle Ages contributed to the discovery of atoms.
- Dalton established his atomic theory based on the fact that the masses of reactants in specific chemical reactions always have a particular mass ratio.
- J. J. Thomson, who discovered the electron in 1897, proposed the plum pudding model of the atom in 1904 before the discovery of the atomic nucleus in order to include the electron in the atomic model.
- In Thomson's model, the atom is composed of electrons surrounded by a soup of positive charge to balance the electrons' negative charges, like negatively charged "plums" surrounded by positively charged "pudding".
- The 1904 Thomson model was disproved by Hans Geiger's and Ernest Marsden's 1909 gold foil experiment.

- Rutherford overturned Thomson's model in 1911 with his well-known gold foil experiment, in which he demonstrated that the atom has a tiny, high- mass nucleus.
- In his experiment, Rutherford observed that many alpha particles were deflected at small angles while others were reflected back to the alpha source.
- This highly concentrated, positively charged region is named the "nucleus" of the atom.
- According to Bohr: 1) Electrons in atoms orbit the nucleus, 2) The electrons can only orbit stably, without radiating, in certain orbits, and 3) Electrons can only gain and lose energy by jumping from one allowed orbit to another.
- The significance of the Bohr model is that the laws of classical mechanics apply to the motion of the electron about the nucleus only when restricted by a quantum rule. Therefore, his atomic model is called a semiclassical model.
- The laws of classical mechanics predict that the electron should release electromagnetic radiation while orbiting a nucleus, suggesting that all atoms should be unstable!
- Classical electrodynamics predicts that an atom described by a (classical) planetary model would be unstable.
- To explain the hydrogen spectrum, Bohr had to make a few assumptions that electrons could only have certain classical motions.
- After the seminal work by Planck, Einstein, and Bohr, physicists began to realize that it was essential to introduce the notion of " quantization " to explain microscopic worlds.
- The "Bohr orbits" have a very important feature of quantization: that the angular momentum L of an electron in its orbit is quantized, that is, it has only specific, discrete values. This leads to the equation $\mathrm{L} = \mathrm{m_e v r_n} = \mathrm{n}\frac{\mathrm{h}}{2\pi} = \mathrm{n}\hbar$.
- At the time of proposal, Bohr himself did not know why angular momentum should be quantized, but using this assumption he was able to calculate the energies in the hydrogen spectrum.
- A theory of the atom or any other system must predict its energies based on the physics of the system, which the Bohr model was able to do.
- According to Bohr, allowed orbit radius at any n is $\mathrm{r_n} = \frac{\mathrm{n}^2\hbar^2}{Z\mathrm{k}_e\mathrm{e}^2\mathrm{m}_e}$. The smallest possible value of rr in the hydrogen atom is called the Bohr radius and is equal to 0.053 nm.
- The energy of the nn-th level for any atom is $\mathrm{E} = \approx \frac{-13.6\mathrm{Z}^2}{\mathrm{n}^2}\mathrm{eV}$.
- The energy of a photon emitted by a hydrogen atom is given by the difference of two hydrogen energy levels: $\mathrm{E} = \mathrm{E_i} - \mathrm{E_f} = \mathrm{R}\left(\frac{1}{\mathrm{n_f^2}} - \frac{1}{\mathrm{n_i^2}}\right)$, which is known as Rydberg formula.
- Atomic and molecular emission and absorption spectra have been known for over a century to be discrete (or quantized).
- Lyman, Balmer, and Paschen series are named after early researchers who studied them in particular depth.
- Bohr was the first one to provide a theoretical explanation of the hydrogen spectra.
- Bohr's condition, that the angular momentum is an integer multiple of $\hbar\hbar$, was later reinterpreted in 1924 by de Broglie as a standing wave condition.
- For what Bohr was forced to hypothesize as the rule for allowed orbits, de Broglie's matter wave concept explains it as the condition for constructive interference of an electron in a circular orbit.
- Bohr's model was only applicable to hydrogen-like atoms. In 1925, more general forms of description (now called quantum mechanics) emerged, thanks to Heisenberg and Schrodinger.
- Compton derived the mathematical relationship between the shift in wavelength and the scattering angle of the X-rays.
- Compton effects (with electrons) usually occur with x-ray photons.
- If the photon is of lower energy, in the visible light through soft X-rays range, photoelectric effects are observed. Higher energy photons, in the gamma ray range, may lead to pair production.
- X rays are relatively high- frequency EM radiation. They are produced by transitions between inner-shell electron levels, which produce x rays characteristic of the atomic element, or by accelerating electrons.
- x-ray diffraction is a technique that provides the detailed information about crystallographic structure of natural and manufactured materials.
- Current research in material science and physics involves complex materials whose lattice arrangements are crucial to obtaining a superconducting material, which can be studied using x-ray crystallography.

Key Terms

- **scintillation**: A flash of light produced in a transparent material by the passage of a particle.
- **alpha particle**: A positively charged nucleus of a helium-4 atom (consisting of two protons and two neutrons), emitted as a consequence of radioactivity.

- **cathode**: An electrode through which electric current flows out of a polarized electrical device.
- **electromagnetic force**: a long-range fundamental force that acts between charged bodies, mediated by the exchange of photons
- **Avogadro's number**: the number of constituent particles (usually atoms or molecules) in one mole of a given substance. It has dimensions of reciprocal mol and its value is equal to $6.02214129 \cdot 10^{23}\ \mathrm{mol}^{-1}$
- **nucleus**: the massive, positively charged central part of an atom, made up of protons and neutrons
- **Maxwell's equations**: A set of equations describing how electric and magnetic fields are generated and altered by each other and by charges and currents.
- **semiclassical**: a theory in which one part of a system is described quantum-mechanically whereas the other is treated classically.
- **black body**: An idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence. Although black body is a theoretical concept, you can find approximate realizations of black body in nature.
- **photoelectric effect**: The occurrence of electrons being emitted from matter (metals and non-metallic solids, liquids, or gases) as a consequence of their absorption of energy from electromagnetic radiation.
- **quantization**: The process of explaining a classical understanding of physical phenomena in terms of a newer understanding known as quantum mechanics.
- **centripetal**: Directed or moving towards a center.
- **photon**: The quantum of light and other electromagnetic energy, regarded as a discrete particle having zero rest mass, no electric charge, and an indefinitely long lifetime.
- **spectrum**: A condition that is not limited to a specific set of values but can vary infinitely within a continuum. The word saw its first scientific use within the field of optics to describe the rainbow of colors in visible light when separated using a prism.
- **standing wave**: A wave form which occurs in a limited, fixed medium in such a way that the reflected wave coincides with the produced wave. A common example is the vibration of the strings on a musical stringed instrument.
- **matter wave**: A concept reflects the wave-particle duality of matter. The theory was proposed by Louis de Broglie.
- **gamma ray**: A very high frequency (and therefore very high energy) electromagnetic radiation emitted as a consequence of radioactivity.
- **photoelectric effects**: In photoelectric effects, electrons are emitted from matter (metals and non-metallic solids, liquids or gases) as a consequence of their absorption of energy from electromagnetic radiation.

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9.3: Atomic Physics and Quantum Mechanics

learning objectives

- Explain relationship between the wave nature of matter and the quantization of energy levels in bound systems

To consider why wave nature of matter in bound systems leads to quantization, let's consider an example in classical mechanics. We will look at a basic string "instrument" (a string pulled tight and fixed at both ends). If a string was free and not attached to anything, we know that it could oscillate at any driven frequency. However, the string in this example (with fixed ends and specific length) can only produce a very specific set of pitches because only waves of a certain wavelength can "fit" on the string of a given length with fixed ends. Once the string becomes a "bound system" with specific boundary restrictions, it allows waves with only a discrete set of frequencies.

This is the exact mechanism that causes quantization in atoms. The wave nature of matter is responsible for the quantization of energy levels in bound systems. Just like a free string, the matter wave of a free electron can have any wavelength, determined by its momentum. However, once an electron is "bound" by a Coulomb potential of a nucleus, it can no longer have an arbitrary wavelength as the wave needs to satisfy a certain boundary condition. Only those states where matter interferes constructively (leading to standing waves) exist, or are "allowed" (see illustration in.

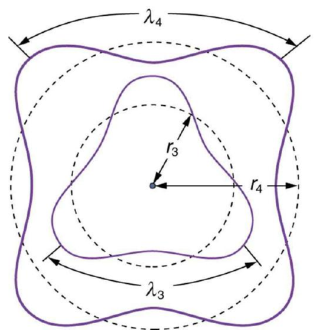


Fig 2: The third and fourth allowed circular orbits have three and four wavelengths, respectively, in their circumferences.

Assuming that an integral multiple of the electron's wavelength equals the circumference of the orbit, we have:

$$\mathrm{n}\lambda_\mathrm{n} = 2\pi \mathrm{r_n} (\mathrm{n} = 1, 2, 3, \ldots) \tag{9.3.1}$$

Substituting $\lambda = \frac{\mathrm{h}}{\mathrm{m_e v}}$, this becomes:

$$\frac{\mathrm{nh}}{\mathrm{m_{ev}}} = 2\pi \mathrm{r_n} \tag{9.3.2}$$

The angular momentum is $\mathrm{L} = \mathrm{m_e vr}$, therefore we obtain the quantization of angular momentum:

$$\mathrm{L} = \mathrm{m_e v r_n} = \mathrm{n}\frac{\mathrm{h}}{2\pi} (\mathrm{n} = 1, 2, 3, \ldots) \tag{9.3.3}$$

As previously discussed, Bohr was forced to hypothesize this as the rule for allowed orbits. We now realize this as a condition for constructive interference of an electron in a (bound) circular orbit.

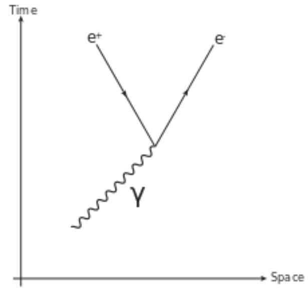
Photon Interactions and Pair Production

Pair production refers to the creation of an elementary particle and its antiparticle, usually when a photon interacts with a nucleus.

learning objectives

- Describe process of pair production as the result of photon interaction with nucleus

Below is an illustration of pair production, which refers to the creation of an elementary particle and its antiparticle, usually when a photon interacts with a nucleus. For example, an electron and its antiparticle, the positron, may be created. This is allowed, provided there is enough energy available to create the pair (i.e., the total rest mass energy of the two particles) and that the situation allows both energy and momentum to be conserved. Some other conserved quantum numbers such as angular momentum, electric charge, etc., must sum to zero as well. The probability of pair production in photon-matter interactions increases with increasing photon energy, and also increases with atomic number (Z) of the nucleus approximately as Z^2.



Pair Production: Feynman diagram for pair production. A photon decays into an electron-positron pair.

$\gamma+\gamma \rightarrow \mathbf{e}^{-}+\mathbf{e}^{+}$

In nuclear physics, this reaction occurs when a high-energy photon (gamma rays) interacts with a nucleus. The energy of this photon can be converted into mass through Einstein's equation $E=mc^2$ where E is energy, mm is mass and c is the speed of light. The photon must have enough energy to create the mass of an electron plus a positron. The mass of an electron is $9.11 \cdot 10^{-31}$ kg (equivalent to 0.511 MeV in energy), the same as a positron.

Without a nucleus to absorb momentum, a photon decaying into electron-positron pair (or other pairs for that matter) can never conserve energy and momentum simultaneously. The nucleus in the process carries away (or provides) access momentum.

The reverse process is also possible. The electron and positron can annihilate and produce two 0.511 MeV gamma photons. If all three gamma rays, the original with its energy reduced by 1.022 MeV and the two annihilation gamma rays, are detected simultaneously, then a full energy peak is observed.

These interactions were first observed in Patrick Blackett's counter-controlled cloud chamber, leading him to receive the 1948 Nobel Prize in Physics.

Key Points

- Strings in musical instruments (guitar, for example) can only produce a very specific set of pitches because only waves of a certain wavelength can "fit" on the string of a given length with fixed ends.
- Similarly, once an electron is bound by a Coulomb potential of a nucleus, it no longer can have any arbitrary wavelength because the wave should satisfy a certain boundary condition.
- Bohr's quantization assumption can be derived from the condition for constructive intereference of an electron matter wave in a circular orbit.
- The probability of pair production in photon -matter interactions increases with increasing photon energy, and also increases with atomic number of the nucleus approximately as Z.
- Energy and momentum should be conserved through the pair production process. Some other conserved quantum numbers such as angular momentum, electric charge, etc., must sum to zero as well.
- Nucleus is needed in the pair production of electron and positron to satisfy the energy and momentum conservation laws.

Key Terms

- **quantization**: The process of explaining a classical understanding of physical phenomena in terms of a newer understanding known as quantum mechanics.
- **angular momentum**: A vector quantity describing an object in circular motion; its magnitude is equal to the momentum of the particle, and the direction is perpendicular to the plane of its circular motion.
- **matter wave**: A concept reflects the wave-particle duality of matter. The theory was proposed by Louis de Broglie.
- **gamma ray**: A very high frequency (and therefore very high energy) electromagnetic radiation emitted as a consequence of radioactivity.
- **positron**: The antimatter equivalent of an electron, having the same mass but a positive charge.

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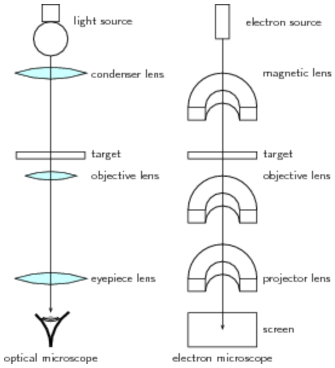
9.4: Applications of Atomic Physics

We have seen that under certain circumstances particles behave like waves. This idea is used in the electron microscope which is a type that uses electrons to create an image of the target. It has much higher magnification or resolving power than a normal light microscope. It can achieve better than 50 pm resolution and magnifications of up to about 10,000,000 times, whereas ordinary, nonconfocal light microscopes are limited by diffraction to about 200 nm resolution and useful magnifications below 2000 times.

Electron Microscope Image: An image of an ant in a scanning electron microscope.

Let's first review how a regular optical microscope works. A beam of light is shone through a thin target and the image is then magnified and focused using objective and ocular lenses. The amount of light which passes through the target depends on its densities, since the less dense regions allow more light to pass through than the denser regions. This means that the beam of light which is partially transmitted through the target carries information about the inner structure of the target.



Optical and Electron Microscopes: Diagram of the basic components of an optical microscope and an electron microscope.

The original form of electron microscopy, transmission electron microscopy, works in a similar manner using electrons. In the electron microscope, electrons which are emitted by a cathode are formed into a beam using magnetic lenses (usually electromagnets). This electron beam is then passed through a very thin target. Again, the regions in the target with higher densities stop the electrons more easily. So, the number of electrons which pass through the different regions of the target depends on their densities. This means that the partially transmitted beam of electrons carries information about the densities of the inner structure of the target.

The spatial variation in this information (the "image") is then magnified by a series of magnetic lenses and it is recorded by hitting a fluorescent screen, photographic plate, or light-sensitive sensor such as a CCD (charge-coupled device) camera. The image detected by the CCD may be displayed in real time on a monitor or computer.

Electron microscopes are very useful as they are able to magnify objects to a much higher resolution. This is because their de Broglie wavelengths are so much smaller than that of visible light. You hopefully remember that light is diffracted by objects which are separated by a distance of about the same size as the wavelength of the light. This diffraction then prevents you from being able to focus the transmitted light into an image.

Therefore, the sizes at which diffraction occurs for a beam of electrons is much smaller than those for visible light. This is why you can magnify targets to a much higher order of magnification using electrons rather than visible light.

Lasers

A laser consists of a gain medium, a mechanism to supply energy to it, and something to provide optical feedback.

learning objectives

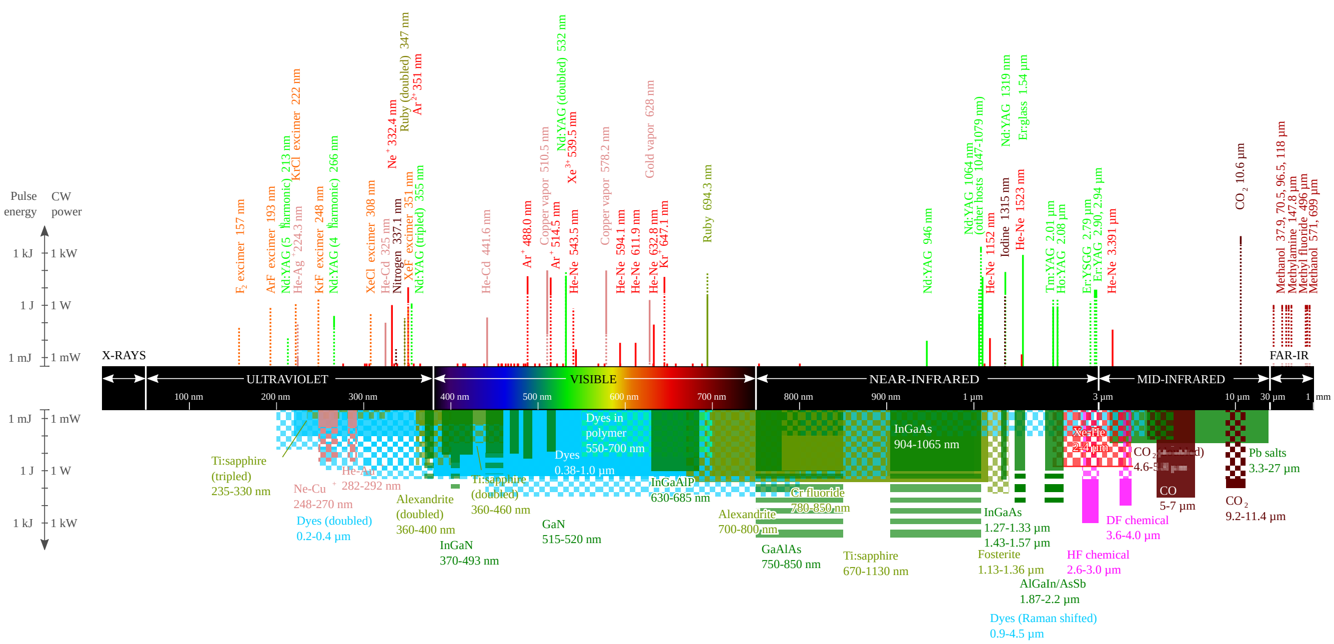
- Describe basic parts of laser

When lasers were invented in 1960, they were called "a solution looking for a problem. " Nowadays, lasers are ubiquitous, finding utility in thousands of highly varied applications in every section of modern society, including consumer electronics, information technology, science, medicine, industry, law enforcement, entertainment, and the military.

Having examined stimulated emission and optical amplification process in the "Lasers, Applications of Quantum Mechanics" section, this atom looks at how lasers are built.

A laser consists of a gain medium, a mechanism to supply energy to it, and something to provide optical feedback (usually an optical cavity). When a gain medium is placed in an optical cavity, a laser can then produce a coherent beam of photons.

The gain medium is where the optical amplification process occurs. It is excited by an external source of energy into an excited state (called "population inversion"), ready to be fired when a photon with the right frequency enters the medium. In most lasers, this medium consists of a population of atoms which have been excited by an outside light source or an electrical field which supplies energy for atoms to absorb in order to be transformed into excited states. There are many types of lasers depending on the gain media and mode of operation. Gas and semiconductors are commonly used gain media.



***Wavelengths of Commercially Available Lasers**: Laser types with distinct laser lines are shown above the wavelength bar, while below are shown lasers that can emit in a wavelength range. The height of the lines and bars gives an indication of the maximal power/pulse energy commercially available, while the color codifies the type of laser material.*

The most common type of laser uses feedback from an optical cavity–a pair of highly reflective mirrors on either end of the gain medium. A single photon can bounce back and forth between the mirrors many times, passing through the gain medium and being amplified each time. Typically one of the two mirrors, the output coupler, is partially transparent. Some of the light escapes through this mirror, producing a laser beam that is visible to the naked eye.

Key Points

- Electron microscopes are very useful as they are able to magnify objects to a much higher resolution than optical ones.
- Higher resolution can be achieved with electron microscopes because the de Broglie wavelengths for electrons are so much smaller than that of visible light.

- In electron microscopes, electromagnets can be used as magnetic lenses to manipulate electron beams.
- The gain medium is where the optical amplification process occurs. Gas and semiconductors are commonly used gain media.
- The most common type of laser uses feedback from an optical cavity–a pair of highly reflective mirrors on either end of the gain medium. A single photon can bounce back and forth between the mirrors many times, passing through the gain medium and being amplified each time.
- Lasers are ubiquitous, finding utility in thousands of highly varied applications in every section of modern society.

Key Terms

- **CCD**: A charge-coupled device (CCD) is a device for the movement of electrical charge, usually from within the device to an area where the charge can be manipulated, for example conversion into a digital value. The CCD is a major technology required for digital imaging.
- **de Broglie wavelength**: The wavelength of a matter wave is inversely proportional to the momentum of a particle and is called a de Broglie wavelength.
- **stimulated emission**: The process by which an atomic electron (or an excited molecular state) interacting with an electromagnetic wave of a certain frequency may drop to a lower energy level, transferring its energy to that field.

9.5: Multielectron Atoms

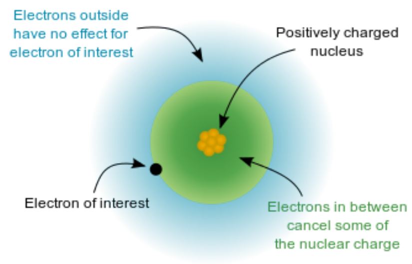
learning objectives

- Describe atomic structure and shielding in multielectron atoms

Multielectron Atoms

Atoms with more than one electron, such as Helium (He) and Nitrogen (N), are referred to as multielectron atoms. Hydrogen is the only atom in the periodic table that has one electron in the orbitals under ground state.

In hydrogen-like atoms (those with only one electron), the net force on the electron is just as large as the electric attraction from the nucleus. However, when more electrons are involved, each electron (in the nn-shell) feels not only the electromagnetic attraction from the positive nucleus, but also repulsion forces from other electrons in shells from '1' to 'nn'. This causes the net force on electrons in the outer electron shells to be significantly smaller in magnitude. Therefore, these electrons are not as strongly bonded to the nucleus as electrons closer to the nucleus. This phenomenon is often referred to as the Orbital Penetration Effect. The shielding theory also explains why valence shell electrons are more easily removed from the atom.



Electron Shielding Effect: A multielectron atom with inner electrons shielding outside electrons from the positively charged nucleus

The size of the shielding effect is difficult to calculate precisely due to effects from quantum mechanics. As an approximation, the effective nuclear charge on each electron can be estimated by: $Z_{eff} = Z - \sigma Z_{\ eff} = Z – \sigma$, where Z is the number of protons in the nucleus and σ\sigma is the average number of electrons between the nucleus and the electron in question. σ\sigma can be found by using quantum chemistry and the Schrodinger equation or by using Slater's empirical formula.

For example, consider a sodium cation, a fluorine anion, and a neutral neon atom. Each has 10 electrons, and the number of nonvalence electrons is two (10 total electrons minus eight valence electrons), but the effective nuclear charge varies because each has a different number of protons:

$$Z_{eff} F^- = 9 - 2 = 7+ \tag{9.5.1}$$

$$Z_{eff} Ne = 10 - 2 = 8+ \tag{9.5.2}$$

$$Z_{eff} Na^+ = 11 - 2 = 9+ \tag{9.5.3}$$

As a consequence, the sodium cation has the largest effective nuclear charge and, therefore, the smallest atomic radius.

The Periodic Table

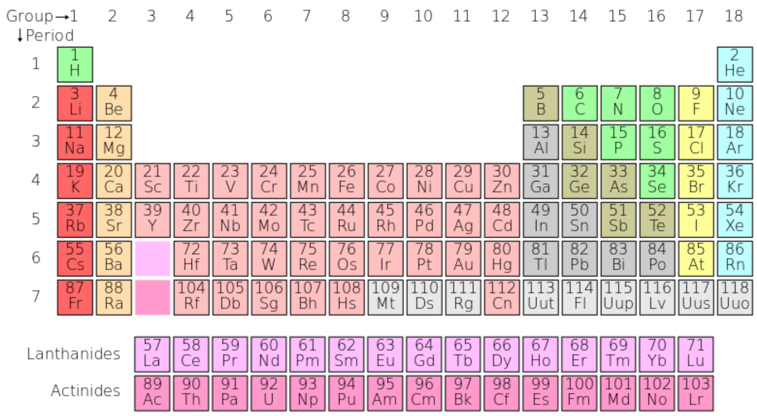
A periodic table is the arrangement of chemical elements according to their electron configurations and recurring chemical properties.

learning objectives

- Explain how elements are arranged in the Periodic Table.

A periodic table is a tabular display of the chemical elements, organized on the basis of their atomic numbers, electron configurations, and recurring chemical properties. Elements are presented according to their atomic numbers (number of protons) in increasing order. The standard form of the table comprises an eighteen by seven grid or main body of elements, positioned above a smaller double row of elements. The table can also be deconstructed into four rectangular blocks: the s-block to the left, the p-block to the right, the d-block in the middle, and the f-block below that. The rows of the table are called periods. The columns of the s-, d-, and p-blocks are called groups, some of which have names such as the halogens or the noble gases.

Since, by definition, a periodic table incorporates recurring trends, any such table can be used to derive relationships between the properties of the elements and predict the properties of new elements that are yet to be discovered or synthesized. As a result, a periodic table, in the standard form or some other variant, provides a useful framework for analyzing chemical behavior. Such tables are widely used in chemistry and other sciences.



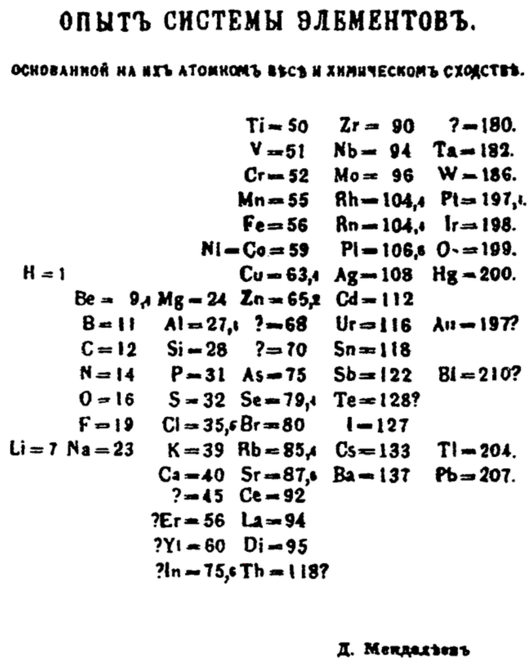
Periodic Table of Elements: The standard form of the periodic table, where the colors represent different categories of elements

The Specifics of the Periodic Table

All versions of the periodic table include only chemical elements, rather than mixtures, compounds, or subatomic particles. Each chemical element has a unique atomic number representing the number of protons in its nucleus. Most elements have differing numbers of neutrons among different atoms: these variants are referred to as isotopes. For example, carbon has three naturally occurring isotopes. All of its atoms have six protons and most have six neutrons as well, but about one percent have seven neutrons, and a very small fraction have eight neutrons. Isotopes are never separated in the periodic table. They are always grouped together under a single element. Elements with no stable isotopes have the atomic masses of their most stable isotopes listed in parentheses.

All elements from atomic numbers ‘1’ (hydrogen) to ‘118’ (ununoctium) have been discovered or synthesized. Of these, elements up through californium exist naturally; the rest have only been synthesized in laboratories. The production of elements beyond ununoctium is being pursued. The question of how the periodic table may need to be modified to accommodate any such additions is a matter of ongoing debate. Numerous synthetic radionuclides of naturally occurring elements have also been produced in laboratories.

Although precursors exist, Dmitri Mendeleev is generally credited with the publication of the first widely recognized periodic table in 1869. He developed his table to illustrate periodic trends in the properties of the elements known at the time. Mendeleev also predicted some properties of then-unknown elements that were expected to fill gaps in the table. Most of his predictions were proved correct when the elements in question were subsequently discovered. Mendeleev’s periodic table has since been expanded and refined with the discovery or synthesis of more new elements and the development of new theoretical models to explain chemical behavior.



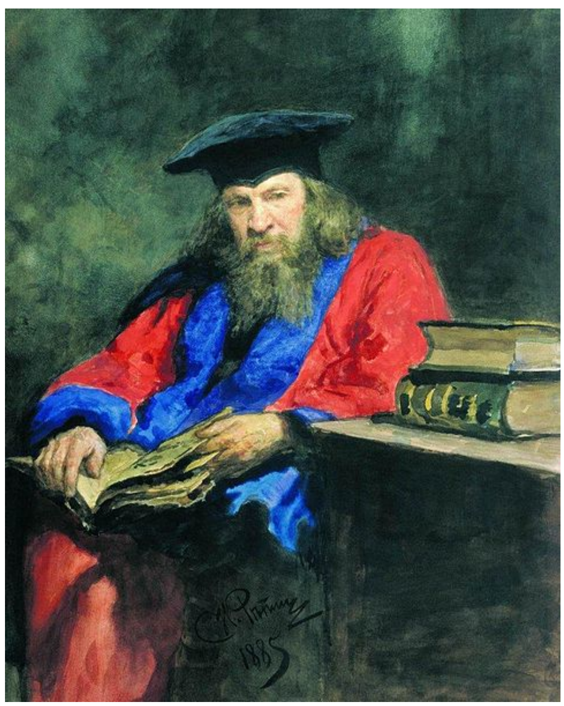
ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ.

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr=90	?=180.
			V=51	Nb=94	Ta=182.
			Cr=52	Mo=96	W=186.
			Mn=55	Rh=104,4	Pt=197,4.
			Fe=56	Rn=104,4	Ir=198.
			Ni=Co=59	Pl=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be=9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ

Mendeleev's 1869 Periodic Table: Mendeleev's 1869 periodic table presents the periods vertically and the groups horizontally.



Dmitri Mendeleev: Dmitri Mendeleev is known for publishing a widely recognized periodic table.

Electron Configurations

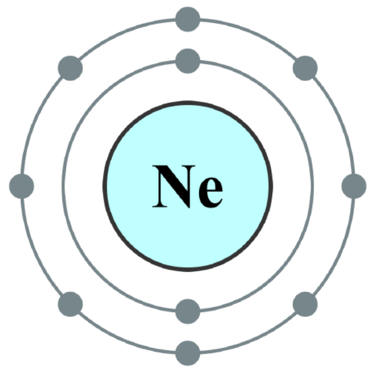
The electron configuration is the distribution of electrons of an atom or molecule in atomic or molecular orbitals.

learning objectives

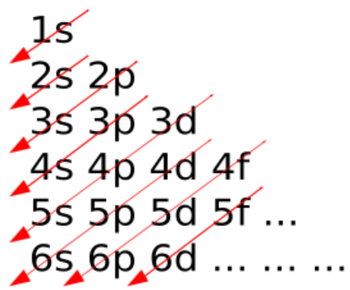
- Explain the meaning of electron configurations

The electron configuration is the distribution of electrons of an atom or molecule in atomic or molecular orbitals. Electron configurations describe electrons as each moving independently in an orbital, in an average field created by all other orbitals.

In atoms, electrons fill atomic orbitals according to the Aufbau principle (shown in), stated as: a maximum of two electrons are put into orbitals in the order of increasing orbital energy—the lowest-energy orbitals are filled before electrons are placed in higher-energy orbitals. As an example, the electron configuration of the neon atom is $1s^2$ $2s^2$ $2p^6$ or [He]$2s^2$ $2p^6$, as diagramed in. In molecules, the situation becomes more complex, as each molecule has a different orbital structure. The molecular orbitals are labelled according to their symmetry, rather than the atomic orbital labels used for atoms and monoatomic ions: hence, the electron configuration of the diatomic oxygen molecule, O_2, is $1\sigma_g{}^2$ $1\sigma_u{}^2$ $2\sigma_g{}^2$ $2\sigma_u{}^2$ $1\pi_u{}^4$ $3\sigma_g{}^2$ $1\pi_g2$.



Electron Configuration of Neon Atom: Electron configuration of neon atom showing only outer electron shell.



Aufbau Principle: In the Aufbau Principle, as electrons are added to atoms, they are added to the lowest orbitals first.

According to the laws of quantum mechanics, for systems with only one electron, an energy is associated with each electron configuration and, upon certain conditions, electrons are able to move from one configuration to another by emission or absorption of a quantum of energy, in the form of a photon.

For atoms or molecules with more than one electron, the motion of electrons are correlated and such picture is no longer exact. An infinite number of electronic configurations are needed to exactly describe any multi-electron system, and no energy can be associated with one single configuration. However, the electronic wave function is usually dominated by a very small number of configurations and therefore the notion of electronic configuration remains essential for multi-electron systems.

Electronic configuration of polyatomic molecules can change without absorption or emission of photon through vibronic couplings.

Knowledge of the electron configuration of different atoms is useful in understanding the structure of the periodic table of elements. The outermost electron shell is often referred to as the valence shell and (to a first approximation) determines the chemical properties. It should be remembered that the similarities in the chemical properties were remarked more than a century before the idea of electron configuration. The concept of electron configuration is also useful for describing the chemical bonds that hold atoms together. In bulk materials this same idea helps explain the peculiar properties of lasers and semiconductors.

Key Points

- Hydrogen is the only atom in the periodic table that has one electron in the orbitals under ground state.
- In multielectron atoms, the net force on electrons in the outer shells is reduced due to shielding.

- The effective nuclear charge on each electron can be approximated as: Zeff=Z−σZeff=Z−σ, where ZZ is the number of protons in the nucleus and σσ is the average number of electrons between the nucleus and the electron in question.
- A periodic table provides a useful framework for analyzing the chemical behavior of elements.
- A periodic table includes only chemical elements with each chemical element assigned a unique atomic number representing the number of protons in its nucleus.
- Dmitri Mendeleev is credited with the publication of the first widely recognized periodic table in 1869.
- Electrons fill atomic orbitals according to the Aufbau principle in atoms.
- For systems with only one electron, an energy is associated with each electron configuration and electrons are able to move from one configuration to another by emission or absorption of a quantum of energy, in the form of a photon.
- For atoms or molecules with more than one electron, an infinite number of electronic configurations are needed to exactly describe any multi-electron system, and no energy can be associated with one single configuration.

Key Terms

- **hydrogen-like**: having a single electron
- **electron shell**: The collective states of all electrons in an atom having the same principal quantum number (visualized as an orbit in which the electrons move).
- **valence shell**: the outermost shell of electrons in an atom; these electrons take part in bonding with other atoms
- **periodic table**: A tabular chart of the chemical elements according to their atomic numbers so that elements with similar properties are in the same column.
- **element**: Any one of the simplest chemical substances that cannot be decomposed in a chemical reaction or by any chemical means and made up of atoms all having the same number of protons.
- **atomic number**: The number, equal to the number of protons in an atom that determines its chemical properties. Symbol: Z
- **atomic orbital**: The quantum mechanical behavior of an electron in an atom describing the probability of the electron's particular position and energy.

Effective_Nuclear_Charge.svg.png. **License**: *CC BY-SA: Attribution-ShareAlike*

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CHAPTER OVERVIEW

10: Nuclear Physics and Radioactivity

Topic hierarchy

10.1: The Nucleus

learning objectives

- Explain relationship between nuclear radius, nuclear density, and nuclear size.

Nuclear size is defined by nuclear radius, also called rms charge radius. It can be measured by the scattering of electrons by the nucleus and also inferred from the effects of finite nuclear size on electron energy levels as measured in atomic spectra.

The problem of defining a radius for the atomic nucleus is similar to the problem of atomic radius, in that neither atoms nor their nuclei have definite boundaries. However, the nucleus can be modelled as a sphere of positive charge for the interpretation of electron scattering experiments: because there is no definite boundary to the nucleus, the electrons "see" a range of cross-sections, for which a mean can be taken. The qualification of "rms" (for "root mean square") arises because it is the nuclear cross-section, proportional to the square of the radius, which is determining for electron scattering.

The first estimate of a nuclear charge radius was made by Hans Geiger and Ernest Marsden in 1909, under the direction of Ernest Rutherford at the Physical Laboratories of the University of Manchester, UK. The famous Rutherford gold foil experiment involved the scattering of α-particles by gold foil, with some of the particles being scattered through angles of more than 90°, that is coming back to the same side of the foil as the α-source, as shown in Figure 1. Rutherford was able to put an upper limit on the radius of the gold nucleus of 34 femtometers (fm).

Later studies found an empirical relation between the charge radius and the mass number, A, for heavier nuclei $(\mathrm{A}>20): \mathrm{R} \approx \mathrm{r} \cdot \mathrm{A}^{1/3}$ where r is an empirical constant of 1.2–1.5 fm. This gives a charge radius for the gold nucleus (A=197A=197) of about 7.5 fm.

Nuclear density is the density of the nucleus of an atom, averaging about $4 \cdot 10^{17} \mathrm{kg/m^3}$. The nuclear density for a typical nucleus can be approximately calculated from the size of the nucleus:

$$\mathrm{n}=\frac{\mathrm{A}}{\frac{4}{3}\pi \mathrm{R}^3} \tag{10.1.1}$$

Nuclear Stability

The stability of an atom depends on the ratio and number of protons and neutrons, which may represent closed and filled quantum shells.

learning objectives

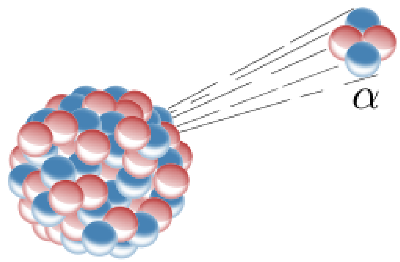
- Explain the relationship between the stability of an atom and its atomic structure.

The stability of an atom depends on the ratio of its protons to its neutrons, as well as on whether it contains a "magic number" of neutrons or protons that would represent closed and filled quantum shells. These quantum shells correspond to energy levels within the shell model of the nucleus. Filled shells, such as the filled shell of 50 protons in the element tin, confers unusual stability on the nuclide. Of the 254 known stable nuclides, only four have both an odd number of protons and an odd number of neutrons:

- hydrogen-2 (deuterium)
- lithium-6
- boron-10
- nitrogen-14

Also, only four naturally occurring, radioactive odd-odd nuclides have a half-life greater than a billion years:

- potassium-40
- vanadium-50
- lanthanum-138
- tantalum-180m



Alpha Decay: Alpha decay is one type of radioactive decay. An atomic nucleus emits an alpha particle and thereby transforms ("decays") into an atom with a mass number smaller by four and an atomic number smaller by two. Many other types of decay are possible.

Most odd-odd nuclei are highly unstable with respect to beta decay because the decay products are even-even and therefore more strongly bound, due to nuclear pairing effects.

An atom with an unstable nucleus, called a radionuclide, is characterized by excess energy available either for a newly created radiation particle within the nucleus or via internal conversion. During this process, the radionuclide is said to undergo radioactive decay. Radioactive decay results in the emission of gamma rays and/or subatomic particles such as alpha or beta particles, as shown in. These emissions constitute ionizing radiation. Radionuclides occur naturally but can also be produced artificially.

All elements form a number of radionuclides, although the half-lives of many are so short that they are not observed in nature. Even the lightest element, hydrogen, has a well-known radioisotope: tritium. The heaviest elements (heavier than bismuth) exist only as radionuclides. For every chemical element, many radioisotopes that do not occur in nature (due to short half-lives or the lack of a natural production source) have been produced artificially.

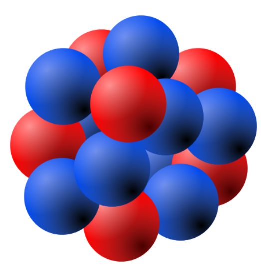
Binding Energy and Nuclear Forces

Nuclear force is the force that is responsible for binding of protons and neutrons into atomic nuclei.

learning objectives

- Explain how nuclear force varies with distance.

The nuclear force is the force between two or more component parts of an atomic nuclei. The component parts are neutrons and protons, which collectively are called nucleons. Nuclear force is responsible for the binding of protons and neutrons into atomic nuclei.



Drawing of Atomic Nucleus: A model of the atomic nucleus showing it as a compact bundle of the two types of nucleons: protons (red) and neutrons (blue).

To disassemble a nucleus into unbound protons and neutrons would require working against the nuclear force. Conversely, energy is released when a nucleus is created from free nucleons or other nuclei—known as the nuclear binding energy. The binding energy of nuclei is always a positive number, since all nuclei require net energy to separate into individual protons and neutrons. Because of mass-energy equivalence (i.e., Einstein's famous formula $E = mc^2$), releasing this energy causes the mass of the nucleus to be lower than the total mass of the individual nucleons (leading to "mass deficit"). Binding energy is the energy used in nuclear power plants and nuclear weapons.

The nuclear force is powerfully attractive between nucleons at distances of about 1 femtometer (fm) between their centers, but rapidly decreases to relative insignificance at distances beyond about 2.5 fm. At very short distances (less than 0.7 fm) it becomes repulsive; it is responsible for the physical size of nuclei since the nucleons can come no closer than the force allows.

The nuclear force is now understood as a residual effect of an even more powerful "strong force" or strong interaction. It is the attractive force that binds together particles known as quarks (to form the nucleons themselves). This more powerful force is mediated by particles called gluons. Gluons hold quarks together with a force like that of an electric charge (but of far greater power).

The nuclear forces arising between nucleons are now seen as analogous to the forces in chemistry between neutral atoms or molecules (called London forces). Such forces between atoms are much weaker than the attractive electrical forces that hold together the atoms themselves (i.e., that bind electrons to the nucleus), and their range between atoms is shorter because they arise from a small separation of charges inside the neutral atom.

Similarly, even though nucleons are made of quarks in combinations which cancel most gluon forces (they are "color neutral"), some combinations of quarks and gluons leak away from nucleons in the form of short-range nuclear force fields that extend from one nucleon to another nucleon in close proximity. These nuclear forces are very weak compared to direct gluon forces ("color forces" or "strong forces") inside nucleons, and the nuclear forces extend over only a few nuclear diameters, falling exponentially with distance. Nevertheless, they are strong enough to bind neutrons and protons over short distances, as well as overcome the electrical repulsion between protons in the nucleus. Like London forces, nuclear forces also stop being attractive, and become repulsive when nucleons are brought too close together.

Key Points

- The first estimate of a nuclear charge radius was made by Hans Geiger and Ernest Marsden in 1909, under the direction of Ernest Rutherford, in the gold foil experiment that involved the scattering of α-particles by gold foil, as shown in Figure 1.
- An empirical relation exists between the charge radius and the mass number, A, for heavier nuclei ($\mathrm{A} > 20$): where r is an empirical constant of 1.2–1.5 fm.
- The nuclear density for a typical nucleus can be approximately calculated from the size of the nucleus: $\mathrm{n} = \frac{\mathrm{A}}{\frac{4}{3}\pi\mathrm{R}^3}$
- Most odd-odd nuclei are highly unstable with respect to beta decay because the decay products are even-even and therefore more strongly bound, due to nuclear pairing effects.
- An atom with an unstable nucleus is characterized by excess energy available either for a newly created radiation particle within the nucleus or via internal conversion.
- All elements form a number of radionuclides, although the half-lives of many are so short that they are not observed in nature.
- The nuclear force is powerfully attractive at distances of about 1 femtometer (fm), rapidly decreases to insignificance at distances beyond about 2.5 fm, and becomes repulsive at very short distances less than 0.7 fm.
- The nuclear force is a residual effect of the a strong interaction that binds together particles called quarks into nucleons.
- The binding energy of nuclei is always a positive number while the mass of an atom 's nucleus is always less than the sum of the individual masses of the constituent protons and neutrons when separated.

Key Terms

- **α-particle**: two protons and two neutrons bound together into a particle identical to a helium nucleus
- **atomic spectra**: emission or absorption lines formed when an electron makes a transition from one energy level of an atom to another
- **nucleus**: the massive, positively charged central part of an atom, made up of protons and neutrons
- **nuclide**: A nuclide (from "nucleus") is an atomic species characterized by the specific constitution of its nucleus — i.e., by its number of protons (Z), its number of neutrons (N), and its nuclear energy state.
- **radionuclide**: A radionuclide is an atom with an unstable nucleus, characterized by excess energy available to be imparted either to a newly created radiation particle within the nucleus or via internal conversion.
- **radioactive decay**: any of several processes by which unstable nuclei emit subatomic particles and/or ionizing radiation and disintegrate into one or more smaller nuclei
- **nucleus**: the massive, positively charged central part of an atom, made up of protons and neutrons
- **quark**: In the Standard Model, an elementary subatomic particle that forms matter. Quarks are never found alone in nature, but combine to form hadrons, such as protons and neutrons.
- **gluon**: A massless gauge boson that binds quarks together to form baryons, mesons and other hadrons; it is associated with the strong nuclear force.

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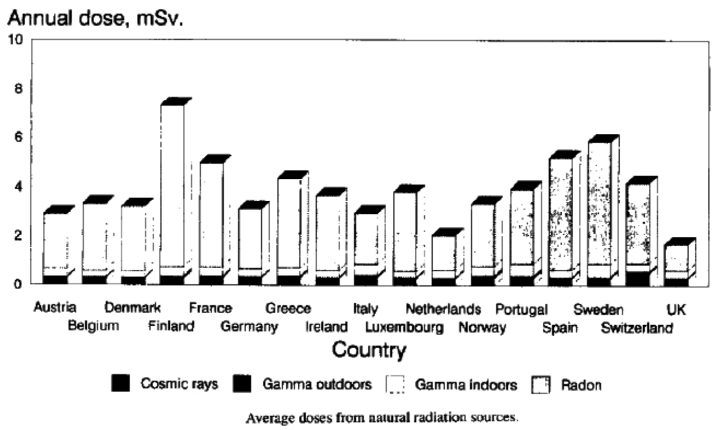
10.2: Radioactivity

Learning objectives

- Name major sources of terrestrial radiation.

Radioactive material is found throughout nature. Detectable amounts occur naturally in soil, rocks, water, air, and vegetation. From these sources it can be inhaled and ingested into the body. In addition to this internal exposure, humans also receive external exposure from radioactive materials that remain outside the body and from cosmic radiation from space. The worldwide average natural dose to humans is about 2.4 millisieverts (mSv) per year. This is four times more than the worldwide average artificial radiation exposure, which in the year 2008 amounted to about 0.6 mSv per year. In some wealthier countries, such as the US and Japan, artificial exposure is, on average, greater than the natural exposure, due to greater access to medical imaging. In Europe, the average natural background exposure by country ranges from under 2 mSv annually in the United Kingdom to more than 7 mSv annually in Finland, as shown in.



Natural Radiation Atlas of Europe: Bar chart of average annual dosages from natural radiation sources for major European countries

Natural Background Radiation

The biggest source of natural background radiation is airborne radon, a radioactive gas that emanates from the ground. Radon and its isotopes, parent radionuclides, and decay products all contribute to an average inhaled dose of 1.26 mSv/a. Radon is unevenly distributed and variable with weather, such that much higher doses occur in certain areas of the world. In these areas it can represent a significant health hazard. Concentrations over 500 times higher than the world average have been found inside buildings in Scandinavia, the United States, Iran, and the Czech Republic. Radon is a decay product of uranium, which is relatively common in the Earth's crust but more concentrated in ore-bearing rocks scattered around the world. Radon seeps out of these ores into the atmosphere or into ground water; it can also infiltrate into buildings. It can be inhaled into the lungs, along with its decay products, where it will reside for a period of time after exposure.

Radiation from Outer Space

In addition, the earth, and all living things on it, are constantly bombarded by radiation from outer space. This radiation primarily consists of positively charged ions ranging from protons to iron and larger nuclei derived from sources outside of our solar system. This radiation interacts with atoms in the atmosphere to create an air shower of secondary radiation, including x-rays, muons, protons, alpha particles, pions, electrons, and neutrons. The immediate dose from cosmic radiation is largely from muons, neutrons, and electrons, and this dose varies in different parts of the world based on the geomagnetic field and altitude. This radiation is much more intense in the upper troposphere (around 10 km in altitude) and is therefore of particular concern for airline crews and frequent passengers, who spend many hours per year in this environment. An airline crew typically gets an extra dose on the order of 2.2 mSv (220 mrem) per year.

Terrestrial Radiation

Terrestrial radiation only includes sources that remain external to the body. The major radionuclides of concern are potassium, uranium, and thorium and their decay products. Some of these decay products, like radium and radon, are intensely radioactive but occur in low concentrations. Most of these sources have been decreasing, due to radioactive decay since the formation of the earth, because there is no significant source of replacement. Because of this, the present activity on Earth from uranium-238 is only half as much as it originally was because of its 4.5-billion-year half-life. Potassium-40 (with a half-life of 1.25 billion years) is at about eight percent of its original activity. However, the effects on humans of the actual diminishment (due to decay) of these isotopes is minimal. This is because humans evolved too recently for the difference in activity over a fraction of a half-life to be significant. Put another way, human history is so short in comparison to a half-life of a billion years that the activity of these long-lived isotopes has been effectively constant throughout our time on this planet.

Many shorter-half-life and therefore more intensely radioactive isotopes have not decayed out of the terrestrial environment because they are still being produced. Examples of these are radium-226 (a decay product of uranium-238) and radon-222 (a decay product of radium-226).

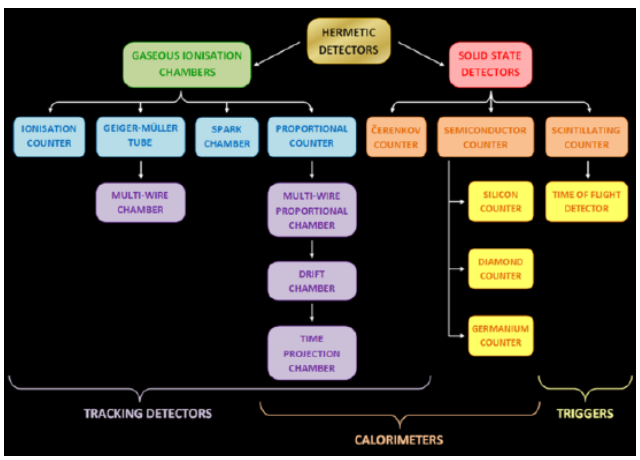
Radiation Detection

A radiation detector is a device used to detect, track, or identify high-energy particles.

Learning objectives

- Explain difference between major types of radiation detectors.

A radiation detector is a device used to detect, track, or identify high- energy particles, such as those produced by nuclear decay, cosmic radiation, and reactions in a particle accelerator. Modern detectors are also used as calorimeters to measure the energy of detected radiation. They may be also used to measure other attributes, such as momentum, spin, and charge of the particles. Different types of radiation detectors exist; gaseous ionization detectors, semiconductor detectors, and scintillation detectors are the most common.



Different Types of Radiation Detectors: different types of radiation detectors (counters)

Gaseous Ionization Detectors

Gaseous ionization detectors use the ionizing effect of radiation upon gas-filled sensors. If a particle has enough energy to ionize a gas atom or molecule, the resulting electrons and ions cause a current flow, which can be measured.

Semiconductor Detectors

A semiconductor detector uses a semiconductor (usually silicon or germanium) to detect traversing charged particles or the absorption of photons. When these detectors' sensitive structures are based on single diodes, they are called semiconductor diode detectors. When they contain many diodes with different functions, the more general term "semiconductor detector" is used. Semiconductor detectors have had various applications in recent decades, in particular in gamma and x-ray spectrometry and as particle detectors.

Scintillation Detectors

A scintillation detector is created by coupling a scintillator — a material that exhibits luminescence when excited by ionizing radiation — to an electronic light sensor, such as a photomultiplier tube (PMT) or a photodiode. PMTs absorb the light emitted by the scintillator and re-emit it in the form of electrons via the photoelectric effect. The subsequent multiplication of those electrons (sometimes called photo-electrons) results in an electrical pulse, which can then be analyzed. The pulse yields meaningful information about the particle that originally struck the scintillator.

Scintillators are used by the American government, particularly Homeland Security, as radiation detectors. Scintillators can also be used in neutron and high-energy particle physics experiments, new energy resource exploration, x-ray security, nuclear cameras, computed tomography, and gas exploration. Other applications of scintillators include CT scanners and gamma cameras in medical diagnostics, screens in computer monitors, and television sets.

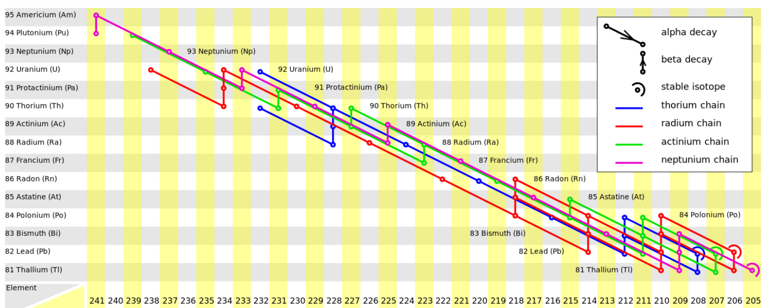
Radioactive Decay Series: Introduction

Radioactive decay series describe the decay of different discrete radioactive decay products as a chained series of transformations.

Learning objectives

- Describe importance of radioactive decay series for decay process.

Radioactive decay series, or decay chains, describe the radioactive decay of different discrete radioactive decay products as a chained series of transformations. Most radioactive elements do not decay directly to a stable state; rather, they undergo a series of decays until eventually a stable isotope is reached.



Radioactive Decay Series Diagram: This diagram provides examples of four decay series: thorium (in blue), radium (in red), actinium (in green), and neptunium (in purple).

Decay stages are referred to by their relationship to previous or subsequent stages. A parent isotope is one that undergoes decay to form a daughter isotope. The daughter isotope may be stable, or it may itself decay to form a daughter isotope of its own. The daughter of a daughter isotope is sometimes called a granddaughter isotope.

The time it takes for a single parent atom to decay to an atom of its daughter isotope can vary widely, not only for different parent-daughter chains, but also for identical pairings of parent and daughter isotopes. While the decay of a single atom occurs spontaneously, the decay of an initial population of identical atoms over time, tt, follows a decaying exponential distribution, e−te−t, where λλis called the decay constant. Because of this exponential nature, one of the properties of an isotope is its half-life, the time by which half of an initial number of identical parent radioisotopes have decayed to their daughters. Half-lives have been determined in laboratories for thousands of radioisotopes (radionuclides). These half-lives can range from nearly nonexistent spans of time to as much as 10^{19} years or more.

The intermediate stages often emit more radioactivity than the original radioisotope. When equilibrium is achieved, a granddaughter isotope is present in proportion to its half-life. But, since its activity is inversely proportional to its half-life, any nuclide in the decay chain finally contributes as much as the head of the chain. For example, natural uranium is not significantly radioactive, but pitchblende, a uranium ore, is 13 times more radioactive because of the radium and other daughter isotopes it contains. Not only are unstable radium isotopes significant radioactivity emitters, but as the next stage in the decay chain they also generate radon, a heavy, inert, naturally occurring radioactive gas. Rock containing thorium and/or uranium (such as some granites) emits radon gas, which can accumulate in enclosed places such as basements or underground mines. Radon exposure is considered the leading cause of lung cancer in non-smokers.

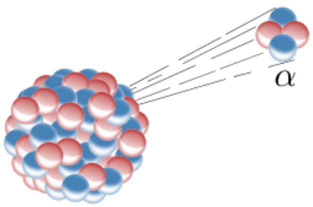
Alpha Decay

In alpha decay an atomic nucleus emits an alpha particle and transforms into an atom with smaller mass (by four) and atomic number (by two).

Learning objectives

- Describe the process, penetration power, and effects of alpha radiation

Alpha decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle that consists of two protons and two neutrons, as shown in. As the result of this process, the parent atom transforms ("decays") into a new atom with a mass number smaller by four and an atomic number smaller by two.



Alpha Decay: Alpha decay is one type of radioactive decay. An atomic nucleus emits an alpha particle and thereby transforms ("decays") into an atom with a mass number smaller by four and an atomic number smaller by two. Many other types of decay are possible.

For example: $238\mathrm{U} \rightarrow 234\mathrm{Th} + \alpha$

Because an alpha particle is the same as a helium-4 nucleus, which has mass number 4 and atomic number 2, this can also be written as:

238

$92\mathrm{U} \rightarrow 234$

$90\mathrm{Th} + 4$

$2\mathrm{He}$

The alpha particle also has charge +2, but the charge is usually not written in nuclear equations, which describe nuclear reactions without considering the electrons. This convention is not meant to imply that the nuclei necessarily occur in neutral atoms.

Alpha decay is by far the most common form of cluster decay, in which the parent atom ejects a defined daughter collection of nucleons, leaving another defined product behind (in nuclear fission, a number of different pairs of daughters of approximately equal size are formed). Alpha decay is the most common cluster decay because of the combined extremely high binding energy and relatively small mass of the helium-4 product nucleus (the alpha particle).

Alpha decay typically occurs in the heaviest nuclides. In theory it can occur only in nuclei somewhat heavier than nickel (element 28), in which overall binding energy per nucleon is no longer a minimum and the nuclides are therefore unstable toward spontaneous fission-type processes. The lightest known alpha emitters are the lightest isotopes (mass numbers 106-110) of tellurium (element 52).

Alpha particles have a typical kinetic energy of 5 MeV (approximately 0.13 percent of their total energy, i.e., 110 TJ/kg) and a speed of 15,000 km/s. This corresponds to a speed of around 0.05 c. There is surprisingly small variation in this energy, due to the heavy dependence of the half-life of this process on the energy produced.

Because of their relatively large mass, +2 electric charge, and relatively low velocity, alpha particles are very likely to interact with other atoms and lose their energy, so their forward motion is effectively stopped within a few centimeters of air.

Most of the helium produced on Earth (approximately 99 percent of it) is the result of the alpha decay of underground deposits of minerals containing uranium or thorium. The helium is brought to the surface as a byproduct of natural gas production.

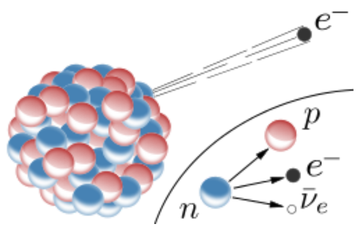
Beta Decay

Beta decay is a type of radioactive decay in which a beta particle (an electron or a positron) is emitted from an atomic nucleus.

Learning objectives

- Explain difference between beta minus and beta plus decays.

Beta decay is a type of radioactive decay in which a beta particle (an electron or a positron) is emitted from an atomic nucleus, as shown in. Beta decay is a process that allows the atom to obtain the optimal ratio of protons and neutrons.



Beta Decay: β decay in an atomic nucleus (the accompanying antineutrino is omitted). The inset shows beta decay of a free neutron

There are two types of beta decay. Beta minus (β) leads to an electron emission (e^-); beta plus (β+) leads to a positron emission (e^+). In electron emission an electron antineutrino is also emitted, while positron emission is accompanied by an electron neutrino. Beta decay is mediated by the weak force.

Emitted beta particles have a continuous kinetic energy spectrum, ranging from 0 to the maximal available energy (Q), that depends on the parent and daughter nuclear states that participate in the decay. The continuous energy spectra of beta particles occur because Q is shared between a beta particle and a neutrino. A typical Q is around 1 MeV, but it can range from a few keV to a several tens of MeV. Since the rest mass energy of the electron is 511 keV, the most energetic beta particles are ultrarelativistic, with speeds very close to the speed of light.

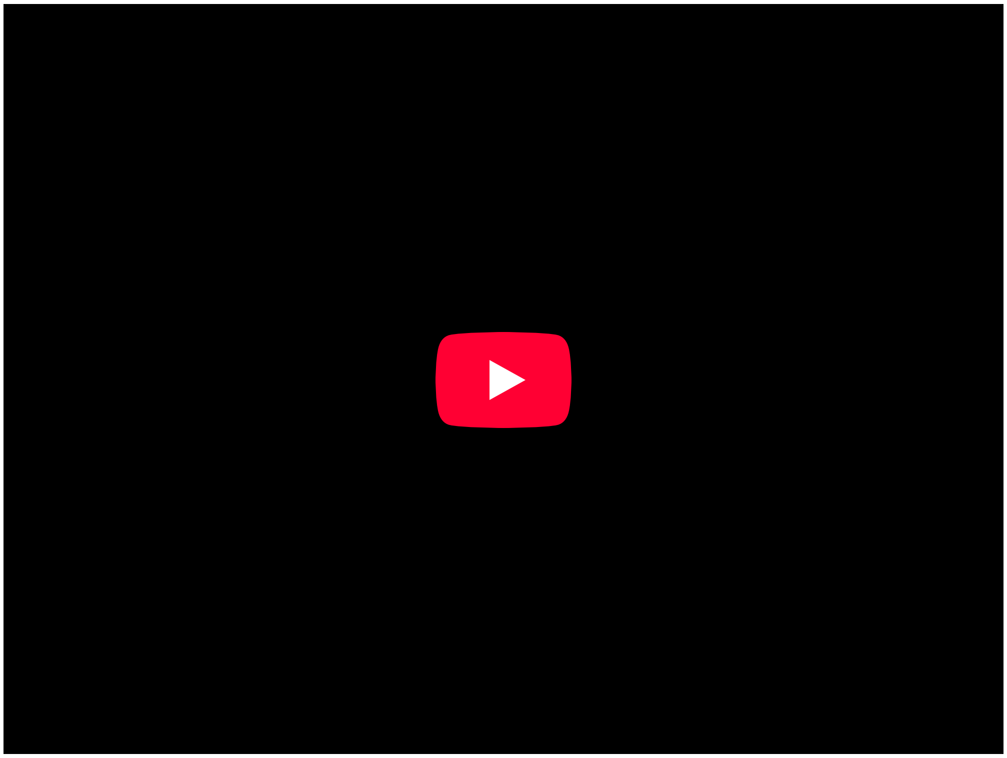
Since the proton and neutron are part of an atomic nucleus, beta decay processes result in transmutation of one chemical element into another. For example:

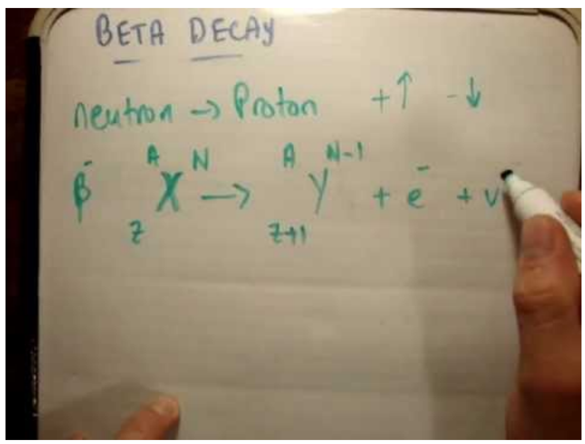
$$137\mathrm{Cs} \rightarrow 137\mathrm{Ba} + \mathrm{e}^- \tag{10.2.1}$$

$$11\mathrm{Na} \rightarrow 10\mathrm{Ne} + \mathrm{e}^+ \tag{10.2.2}$$

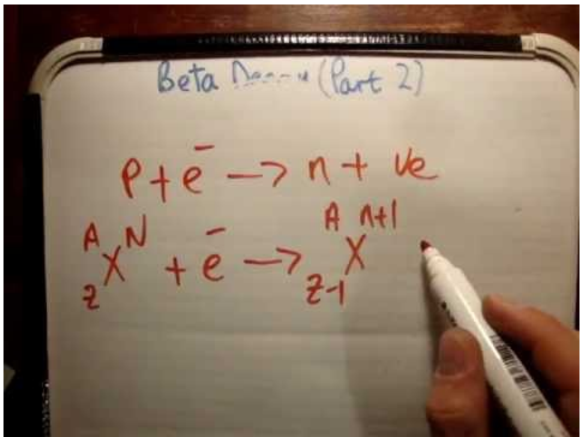
Beta decay does not change the number of nucleons, *A*, in the nucleus; it changes only its charge, *Z*. Therefore the set of all nuclides with the same *A* can be introduced; these isobaric nuclides may turn into each other via beta decay.

A beta-stable nucleus may undergo other kinds of radioactive decay (for example, alpha decay). In nature, most isotopes are beta-stable, but there exist a few exceptions with half-lives so long that they have not had enough time to decay since the moment of their nucleosynthesis. One example is the odd-proton odd-neutron nuclide 40 K, which undergoes both types of beta decay with a half-life of $1.277 \cdot 10^9$ years.





Beta Decay 1/2: In this video I introduce Beta decay and discuss it from an basic level to a perhaps second or third year University level.



Beta Decay 2/2: In this video I introduce Beta decay and discuss it from an basic level to a perhaps second or third year University level.

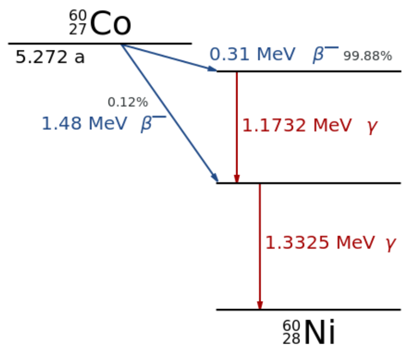
Gamma Decay

Gamma decay is a process of emission of gamma rays that accompanies other forms of radioactive decay, such as alpha and beta decay.

Learning objectives

- Explain relationship between gamma decay and other forms of nuclear decay.

Gamma radiation, also known as gamma rays and denoted as γγ, is electromagnetic radiation of high frequency and therefore high energy. Gamma rays typically have frequencies above 10 exahertz (>1019>1019 Hz) and therefore have energies above 100 keV and wavelengths less than 10 picometers (less than the diameter of an atom). However, this is not a strict definition; rather, it is a rule-of-thumb description for natural processes. Gamma rays from radioactive decay are defined as gamma rays no matter what their energy, so there is no lower limit to gamma energy derived from radioactive decay. Gamma decay commonly produces energies of a few hundred keV and usually less than 10 MeV.



Cobalt-60 Decay Scheme: Path of decay of Co-60 to Ni-60. Excited levels for Ni-60 that drop to ground state via emission of gamma rays are indicated

Gamma decay accompanies other forms of decay, such as alpha and beta decay; gamma rays are produced after the other types of decay occur. When a nucleus emits an α or β particle, the daughter nucleus is usually left in an excited state. It can then move to a lower energy state by emitting a gamma ray, in much the same way that an atomic electron can jump to a lower energy state by emitting a photon. For example, cobalt-60 decays to excited nickel-60 by beta decay through emission of an electron of 0.31 MeV. Next, the excited nickel-60 drops down to the ground state by emitting two gamma rays in succession (1.17 MeV, then 1.33 MeV), as shown in. Emission of a gamma ray from an excited nuclear state typically requires only 10−1210−12 seconds: it is nearly instantaneous. Gamma decay from excited states may also follow nuclear reactions such as neutron capture, nuclear fission, or nuclear fusion.

In certain cases, the excited nuclear state following the emission of a beta particle may be more stable than average; in these cases it is termed a metastable excited state if its decay is 100 to 1000 times longer than the average 10−1210−12 seconds. Such nuclei have half-lives that are easily measurable; these are termed nuclear isomers. Some nuclear isomers are able to stay in their excited state for minutes, hours, or days, or occasionally far longer, before emitting a gamma ray. This phenomenon is called isomeric transition. The process of isomeric transition is therefore similar to any gamma emission; it differs only in that it involves the intermediate metastable excited states of the nuclei.

Half-Life and Rate of Decay; Carbon-14 Dating

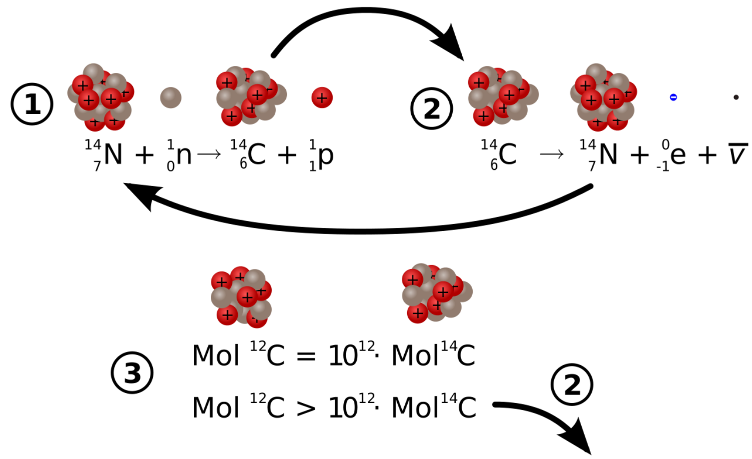
Carbon-14 dating is a radiometric dating method that uses the radioisotope carbon-14 (14C) to estimate the age of object.

Learning objectives

- Identify the age of materials that can be approximately determined using radiocarbon dating

Radiocarbon dating (usually referred to simply as carbon-14 dating) is a radiometric dating method. It uses the naturally occurring radioisotope carbon-14 (14C) to estimate the age of carbon-bearing materials up to about 58,000 to 62,000 years old.

Carbon has two stable, nonradioactive isotopes: carbon-12 (12C) and carbon-13 (13C). There are also trace amounts of the unstable radioisotope carbon-14 (14C) on Earth. Carbon-14 has a relatively short half-life of 5,730 years, meaning that the fraction of carbon-14 in a sample is halved over the course of 5,730 years due to radioactive decay to nitrogen-14. The carbon-14 isotope would vanish from Earth’s atmosphere in less than a million years were it not for the constant influx of cosmic rays interacting with molecules of nitrogen (N_2) and single nitrogen atoms (N) in the stratosphere. Both processes of formation and decay of carbon-14 are shown in.



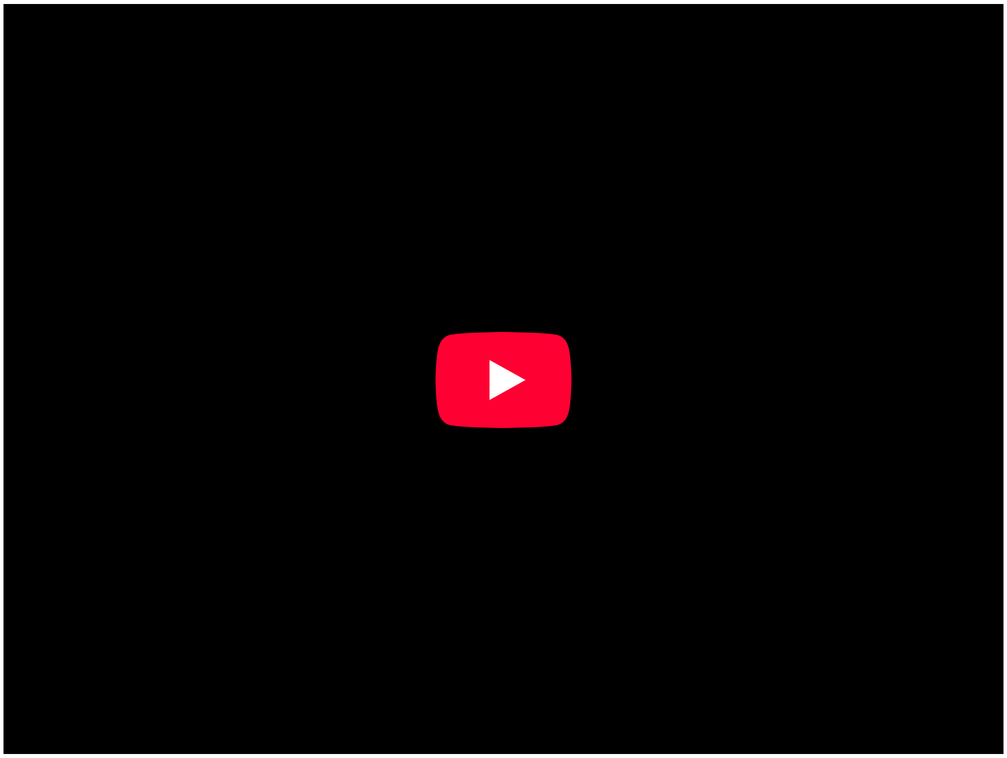
$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p \qquad ^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + \overline{\nu}$$

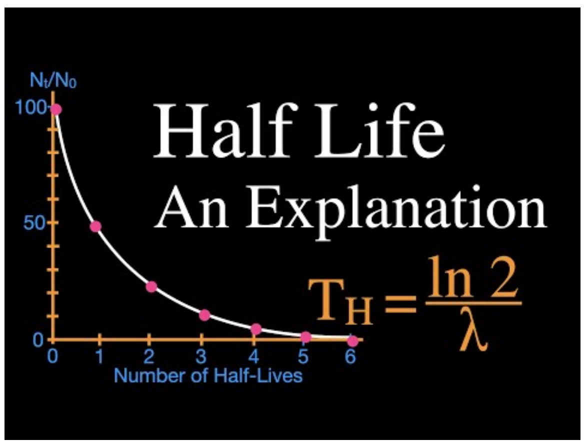
Formation and Decay of Carbon-14: Diagram of the formation of carbon-14 (1), the decay of carbon-14 (2), and equations describing the carbon-12:carbon-14 ratio in living and dead organisms

When plants fix atmospheric carbon dioxide (CO_2) into organic compounds during photosynthesis, the resulting fraction of the isotope 14C in the plant tissue will match the fraction of the isotope in the atmosphere. After plants die or are consumed by other organisms, the incorporation of all carbon isotopes, including 14C, stops. Thereafter, the concentration (fraction) of 14C declines at a fixed exponential rate due to the radioactive decay of 14C. (An equation describing this process is shown in.) Comparing the remaining 14C fraction of a sample to that expected from atmospheric 14C allows us to estimate the age of the sample.

Raw (i.e., uncalibrated) radiocarbon ages are usually reported in radiocarbon years “Before Present” (BP), with “present” defined as CE 1950. Such raw ages can be calibrated to give calendar dates. One of the most frequent uses of radiocarbon dating is to estimate the age of organic remains from archaeological sites.

The technique of radiocarbon dating was developed by Willard Libby and his colleagues at the University of Chicago in 1949. Emilio Segrè asserted in his autobiography that Enrico Fermi suggested the concept to Libby at a seminar in Chicago that year. Libby estimated that the steady-state radioactivity concentration of exchangeable carbon-14 would be about 14 disintegrations per minute (dpm) per gram. In 1960, Libby was awarded the Nobel Prize in chemistry for this work. He demonstrated the accuracy of radiocarbon dating by accurately estimating the age of wood from a series of samples for which the age was known, including an ancient Egyptian royal barge dating from 1850 BCE.





Half-life: Describes radioactive half life and how to do some simple calculations using half life.

Calculations Involving Half-Life and Decay-Rates

The half-life of a radionuclide is the time taken for half the radionuclide's atoms to decay.

Learning objectives

- Explain what is a half-life of a radionuclide.

The half-life of a radionuclide is the time taken for half of the radionuclide's atoms to decay. Taking $\lambda\lambda$ to be the decay rate (number of disintegrations per unit time), and $\tau\tau$ the average lifetime of an atom before it decays, we have:

$$N(t) = N_0 e^{-\lambda t} = N_0 e^{-t/\tau} \tag{10.2.3}$$

The half-life is related to the decay constant by substituting the condition $N = N_o/2$ and solving for $t = t_{1/2}$:

$$t_{1/2} = \ln 2/\lambda = \tau \ln 2 \tag{10.2.4}$$

A half-life must not be thought of as the time required for exactly half of the atoms to decay.

Radioactive decay simulation: A simulation of many identical atoms undergoing radioactive decay, starting with four atoms (left) and 400 atoms (right). The number at the top indicates how many half-lives have elapsed

The following figure shows a simulation of many identical atoms undergoing radioactive decay. Note that after one half-life there are not exactly one-half of the atoms remaining; there are only *approximately*one-half left because of the random variation in the process. However, with more atoms (the boxes on the right), the overall decay is smoother and less random-looking than with fewer atoms (the boxes on the left), in accordance with the law of large numbers.

The relationship between the half-life and the decay constant shows that highly radioactive substances are quickly spent while those that radiate weakly endure longer. Half-lives of known radionuclides vary widely, from more than 10^{19} years, such as for the very nearly stable nuclide 209 Bi, to 10^{-23} seconds for highly unstable ones.

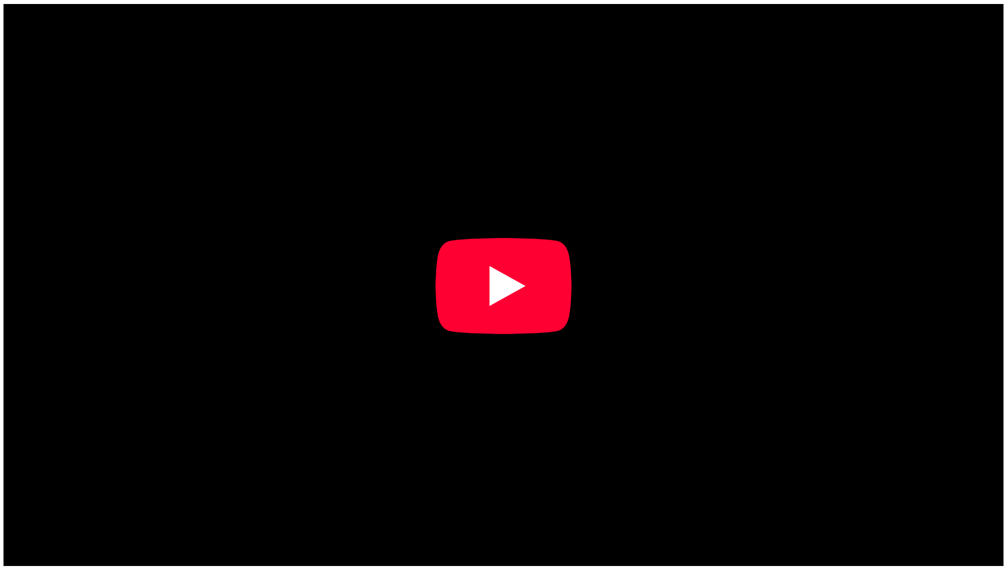
The factor of ln(2) in the above equations results from the fact that the concept of “half-life” is merely a way of selecting a different base other than the natural base *e* for the lifetime expression. The time constant $\tau$is the e^{-1}-life, the time until only 1/*e* remains — about 36.8 percent, rather than the 50 percent in the half-life of a radionuclide. Therefore, $\tau$is longer than $t_{1/2}$. The following equation can be shown to be valid:

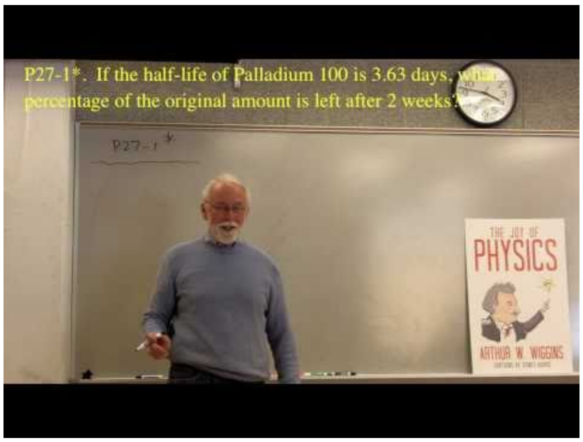
$$\mathrm{N(t) = N_0 e^{-t/\tau} = N_0 2^{-t/t_{1/2}}} \tag{10.2.5}$$

Since radioactive decay is exponential with a constant probability, each process could just as easily be described with a different constant time period that (for example) gave its 1/3-life (how long until only 1/3 is left), or its 1/10-life (how long until only 1/10 is left), and so on. Therefore, the choice of $\tau$and $t_{1/2}$ for marker-times is only for convenience and for the sake of uploading convention. These marker-times reflect a fundamental principle only in that they show that the same proportion of a given radioactive substance will decay over any time period you choose.

Mathematically, the *n*th life for the above situation would be found by the same process shown above — by setting $\mathrm{N = N_0/n}$ and substituting into the decay solution, to obtain:

$$\mathrm{t_{1/n} = \frac{\ln n}{\lambda} = \tau \ln n} \tag{10.2.6}$$





Half-life: Part of a series of videos on physics problem-solving. The problems are taken from “The Joy of Physics. ” This one deals with radioactive half-life. The viewer is urged to pause the video at the problem statement and work the problem before watching the rest of the video.

Key Points

- The biggest source of natural background radiation is airborne radon, a radioactive gas that emanates from the ground.
- The earth is constantly bombarded by radiation from outer space that consists of positively charged ions ranging from protons to iron and larger nuclei from sources outside of our solar system.
- Terrestrial radiation includes sources that remain external to the body. The major radionuclides of concern are potassium, uranium, and thorium and their decay products.
- Gaseous ionization detectors use the ionizing effect of radiation upon gas-filled sensors.
- A semiconductor detector uses a semiconductor (usually silicon or germanium) to detect traversing charged particles or the absorption of photons.
- A scintillation detector is created by coupling a scintillator to an electronic light sensor.
- Most radioactive elements do not decay directly to a stable state; rather, they undergo a series of decays until eventually a stable isotope is reached.
- Half-lives of radioisotopes range from nearly nonexistent spans of time to as much as 1019 years or more.
- The intermediate stages of radioactive decay series often emit more radioactivity than the original radioisotope.
- An alpha particle is the same as a helium-4 nucleus, which has mass number 4 and atomic number 2.
- Because of their relatively large mass, +2 electric charge, and relatively low velocity, alpha particles are very likely to interact with other atoms and lose their energy, so their forward motion is effectively stopped within a few centimeters of air.

- Most of the helium produced on Earth (approximately 99 percent of it) is the result of the alpha decay of underground deposits of minerals containing uranium or thorium.
- There are two types of beta decay: beta minus, which leads to an electron emission, and beta plus, which leads to a positron emission.
- Beta decay allows the atom to obtain the optimal ratio of protons and neutrons.
- Beta decay processes transmute one chemical element into another.
- Gamma decay accompanies other forms of decay, such as alpha and beta decay; gamma rays are produced after the other types of decay occur.
- Although emission of gamma ray is a nearly instantaneous process, it can involve intermediate metastable excited states of the nuclei.
- Gamma rays are generally the most energetic form of electromagnetic radiation.
- Carbon-14 dating can be used to estimate the age of carbon-bearing materials up to about 58,000 to 62,000 years old.
- The carbon-14 isotope would vanish from Earth's atmosphere in less than a million years were it not for the constant influx of cosmic rays interacting with atmospheric nitrogen.
- One of the most frequent uses of radiocarbon dating is to estimate the age of organic remains from archaeological sites.
- The half-life is related to the decay constant as follows: $\mathrm{t}_{1/2} = \ln 2/\lambda$.
- The relationship between the half-life and the decay constant shows that highly radioactive substances are quickly spent while those that radiate weakly endure longer.
- Half-lives of known radionuclides vary widely, from more than 10^{19} years, such as for the very nearly stable nuclide 209 Bi, to 10^{-23} seconds for highly unstable ones.

Key Terms

- **radionuclide**: A radionuclide is an atom with an unstable nucleus, characterized by excess energy available to be imparted either to a newly created radiation particle within the nucleus or via internal conversion.
- **radon**: a radioactive chemical element (symbol Rn, formerly Ro) with atomic number 86; one of the noble gases
- **sievert**: in the International System of Units, the derived unit of radiation dose; the dose received in one hour at a distance of 1 cm from a point source of 1 mg of radium in a 0.5 mm thick platinum enclosure; symbol: Sv
- **scintillator**: any substance that glows under the action of photons or other high-energy particles
- **diode**: an electronic device that allows current to flow in one direction only; a valve
- **semiconductor**: A substance with electrical properties intermediate between a good conductor and a good insulator.
- **half-life**: the time required for half of the nuclei in a sample of a specific isotope to undergo radioactive decay
- **radioisotope**: a radioactive isotope of an element
- **decay**: to change by undergoing fission, by emitting radiation, or by capturing or losing one or more electrons
- **alpha particle**: A positively charged nucleus of a helium-4 atom (consisting of two protons and two neutrons), emitted as a consequence of radioactivity; α-particle.
- **radioactive decay**: any of several processes by which unstable nuclei emit subatomic particles and/or ionizing radiation and disintegrate into one or more smaller nuclei
- **beta decay**: a nuclear reaction in which a beta particle (electron or positron) is emitted
- **positron**: The antimatter equivalent of an electron, having the same mass but a positive charge.
- **transmutation**: the transformation of one element into another by a nuclear reaction
- **electromagnetic radiation**: radiation (quantized as photons) consisting of oscillating electric and magnetic fields oriented perpendicularly to each other, moving through space
- **gamma ray**: A very high frequency (and therefore very high energy) electromagnetic radiation emitted as a consequence of radioactivity.
- **radiometric dating**: Radiometric dating is a technique used to date objects based on a comparison between the observed abundance of a naturally occurring radioactive isotope and its decay products using known decay rates.
- **carbon-14**: carbon-14 is a radioactive isotope of carbon with a nucleus containing 6 protons and 8 neutrons.
- **radionuclide**: A radionuclide is an atom with an unstable nucleus, characterized by excess energy available to be imparted either to a newly created radiation particle within the nucleus or via internal conversion.

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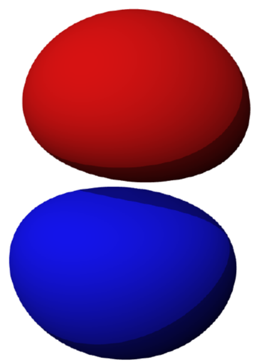
10.3: Quantum Tunneling and Conservation Laws

learning objectives

- Identify factors that affect the tunneling probability

Imagine throwing a ball at a wall and having it disappear the instant before it makes contact and appear on the other side. The wall remains intact; the ball did not break through it. Believe it or not, there is a finite (if extremely small) probability that this event would occur. This phenomenon is called quantum tunneling.

While the possibility of tunneling is essentially ignorable at macroscopic levels, it occurs regularly on the nanoscale level. Consider, for example, a p-orbital in an atom. Between the two lobes there is a nodal plane. By definition there is precisely 0 probability of finding an electron anywhere along that plane, and because the plane extends infinitely it is impossible for an electron to go around it. Yet, electrons commonly cross from one lobe to the other via quantum tunneling. They never exist in the nodal area (this is forbidden); instead they travel through imaginary space.



P-Orbital: The red and blue lobes represent the volume in which there is a 90 percent probability of finding an electron at any given time if the orbital is occupied.

Imaginary space is not real, but it is explicitly referenced in the time-dependent Schrödinger equation, which has a component of ii (the square root of −1−1, an imaginary number):

$$i\hbar \frac{\partial}{\partial t} \Psi = \hat{H} \Psi \tag{10.3.1}$$

And because all matter has a wave component (see the topic of wave-particle duality), all matter can in theory exist in imaginary space. But what accounts for the difference in probability of an electron tunneling over a nodal plane and a ball tunneling through a brick wall? The answer is a combination of the tunneling object's mass (mm) and energy (EE) and the energy height (U0U0) of the barrier through which it must travel to get to the other side.

When it reaches a barrier it cannot overcome, a particle's wave function changes from sinusoidal to exponentially diminishing in form. The solution for the Schrödinger equation in such a medium is:

$$\Psi = A e^{-\alpha x} \tag{10.3.2}$$

where:

$$\alpha = \sqrt{\frac{2m\left(U_0 - E\right)}{h^2}} \tag{10.3.3}$$

Therefore, the probability of an object tunneling through a barrier decreases with the object's increasing mass and with the increasing gap between the energy of the object and the energy of the barrier. And although the wave function never quite reaches 0 (as can be determined from the e−xe−x functionality), this explains how tunneling is frequent on nanoscale but negligible at the macroscopic level.

Conservation of Nucleon Number and Other Laws

Through radioactive decay, nuclear fusion and nuclear fission, the number of nucleons (sum of protons and neutrons) is always held constant.

learning objectives

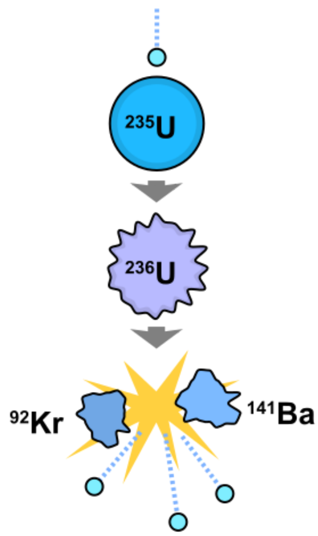
- Define the Law of Conservation of Nuclear Number

In physics and chemistry there are many conservation laws—among them, *the Law of Conservation of Nucleon Number*, which states that the total number of nucleons (nuclear particles, specifically protons and neutrons) cannot change by any nuclear reaction.

Radioactive Decay

Consider the three modes of decay. In gamma decay, an excited nucleus releases gamma rays, but its proton (Z) and neutron (A-Z) count remain the same:

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z}N + \gamma \tag{10.3.4}$$



Nuclear fission of U-235: If U-235 is bombarded with a neutron (light blue small circe), the resulting U-236 produced is unstable and undergoes fission. The resulting elements (shown here as Kr-92 and Ba-141) do not contain as many nucleons as U-236, with the remaining three neutrons being released as high-energy particles, able to bombard another U-235 atom and maintain a chain reaction.

In beta decay, a nucleus releases energy and either an electron or a positron. In the case of an electron being released, atomic mass (A) remains the same as a neutron is converted into a proton, raising atomic number by 1:

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N + e^{-} + \nu \tag{10.3.5}$$

In the case of a positron being released, atomic mass remains constant as a proton is converted to a neutron, lowering atomic number by 1:

$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z-1}N + e^{+} + \nu \tag{10.3.6}$$

Electron capture has the same effect on the number of protons and neutrons in a nucleus as positron emission.

Alpha decay is the only type of radioactive decay that results in an appreciable change in an atom ‘s atomic mass. However, rather than being destroyed, the two protons and two neutrons an atom loses in alpha decay are released as a helium nucleus.

Nuclear Fission

Chain reactions of nuclear fission release a tremendous amount of energy, but follow the Law of Conservation of Nucleon Number. Consider, for example, the multistep reaction that occurs when a U-235 nucleus accepts a neutron, as in:

$$ {}^1_0\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3{}^1_0\mathrm{n} + \gamma \tag{10.3.7} $$

In each step, the total atomic mass of all species is a constant value of 236. This is the same with all fission reactions.

Nuclear Fusion

Finally, nuclear fusion follows the Law of Conservation of Nucleon Number. Consider the fusion of deuterium and tritium (both hydrogen isotopes):

$$ {}^2_1\mathrm{H} + {}^3_1\mathrm{H} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} \tag{10.3.8} $$

It is well understood that the tremendous amounts of energy released by nuclear fission and fusion can be attributed to the conversion of mass to energy. However, the mass that is converted to energy is rather small compared to any sample, and never includes the conversion of a proton or neutron to energy. Thus, the number of nucleons before and after fission and fusion is always constant.

Key Points

- Quantum tunneling applies to all objects facing any barrier. However, the probability of its occurrence is essentially negligible for macroscopic purposes; it is only ever observed to any appreciable degree on the nanoscale level.
- Quantum tunneling is explained by the imaginary component of the Schrödinger equation. Because the wave function of any object contains an imaginary component, it can exist in imaginary space.
- Tunneling decreases with the increasing mass of the object that must tunnel and with the increasing gap between the object's energy and the energy of the barrier it must overcome.
- The law of Conservation of Nuclear Number states that the sum of protons and neutrons among species before and after a nuclear reaction will be the same.
- In radioactive decay, a proton can be converted to a neutron and a neutron can be converted to a proton (beta-decay).
- Nuclear fusion and fission involve the conversion of matter to energy, but the matter that is converted is never a full nucleon.

Key Terms

- **tunneling**: the quantum-mechanical passing of a particle through an energy barrier
- **fusion**: A nuclear reaction in which nuclei combine to form more massive nuclei with the concomitant release of energy.
- **fission**: The process of splitting the nucleus of an atom into smaller particles; nuclear fission.
- **nucleon**: One of the subatomic particles of the atomic nucleus (i.e., a proton or a neutron).

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10.4: Applications of Nuclear Physics

Example 10.4.1:

The nuclear medicine whole body bone scan is generally used in evaluations of various bone related pathology, such as for bone pain, stress fracture, nonmalignant bone lesions, bone infections, or the spread of cancer to the bone.

Radiation therapy involves the application of ionizing radiation to treat conditions such as hyperthyroidism, thyroid cancer, and blood disorders. Radiation therapy is particularly effective as a treatment of a number of types of cancer if they are localized to one area of the body. It may also be used as part of curative therapy, to prevent tumor recurrence after surgery, or to remove a primary malignant tumor. Radiation therapy is synergistic with chemotherapy and has been used before, during, and after chemotherapy in susceptible cancers.

Ionizing radiation works by damaging the DNA of exposed tissue, leading to cellular death. When external beam therapy is used, shaped radiation beams are aimed from several angles of exposure to intersect at the tumor, providing a much larger absorbed dose there than in the surrounding, healthy tissue.

External Beam Therapy: Radiation therapy of the pelvis. Lasers and a mold under the legs are used for precise positioning

Brachytherapy is another form of radiation therapy, in which a therapeutic radioisotope is injected into the body to chemically localize to the tissue that requires destruction . A key feature of brachytherapy is that the irradiation affects only a very localized area around the radiation sources. Exposure to radiation of healthy tissues further away from the sources is therefore reduced in this technique.

Radiation therapy is in itself painless. Many low-dose palliative treatments (for example, radiation therapy targeting bony metastases) cause minimal or no side effects, although short-term pain flare-ups can be experienced in the days following treatment due to edemas compressing nerves in the treated area. Higher doses can cause varying side effects during treatment (acute), in the months or years following treatment (long-term), or after re-treatment (cumulative). The nature, severity, and longevity of side effects depend on the organs that receive the radiation, the treatment itself (type of radiation, dose, fractionation, concurrent chemotherapy), and the individual patient.

Dosimetry

Radiation dosimetry is the measurement and calculation of the absorbed dose resulting from the exposure to ionizing radiation.

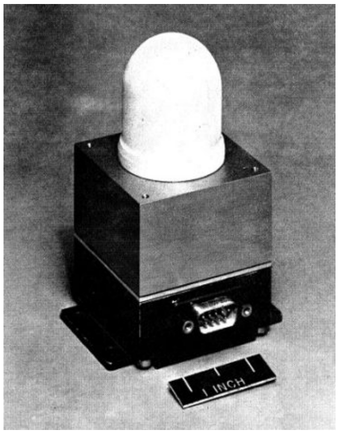
learning objectives

- Explain difference between absorbed dose and dose equivalent.

Radiation dosimetry is the measurement and calculation of the absorbed dose in matter and tissue resulting from the exposure to indirect and direct ionizing radiation.

Measuring Radiation

There are several ways of measuring the dose of ionizing radiation. Workers who come in contact with radioactive substances or who may be exposed to radiation routinely carry personal dosimeters . In the United States, these dosimeters usually contain materials that can be used in thermoluminescent dosimetry or optically stimulated luminescence. Outside the United States, the most widely used type of personal dosimeter is the film badge dosimeter, which uses photographic emulsions that are sensitive to ionizing radiation. The equipment used in radiotherapy (a linear particle accelerator in external beam therapy) is routinely calibrated using ionization chambers or the new and more accurate diode technology. Internal dosimetry is used to evaluate the intake of particles inside a human being.



Ionization Chamber: This ionization chamber was used in the South Atlantic Anomaly Probe project.

Dose is reported in grays (Gy) for absorbed doses or sieverts (Sv) for dose equivalents, where 1 Gy or 1 Sv is equal to 1 joule per kilogram. Non-SI units are still prevalent as well: absorbed dose is often reported in rads and dose equivalent in rems. By definition, 1 Gy = 100 rad, and 1 Sv = 100 rem.

Biological Effects

The distinction between absorbed dose (Gy/rad) and dose equivalent (Sv/rem) is based upon the biological effects. The weighting factor (wr) and tissue/organ weighting factor (WT) have been established. They compare the relative biological effects of various types of radiation and the susceptibility of different organs.

The weighting factor for the whole body is 1, such that 1 Gy of radiation delivered to the whole body is equal to one sievert. Therefore, the WT for all organs in the whole body must sum to 1.

By definition, X-rays and gamma rays have a wr of unity, such that 1 Gy = 1 Sv (for whole-body irradiation). Values of wr are as high as 20 for alpha particles and neutrons. That is to say, for the same absorbed dose in Gy, alpha particles are 20 times as biologically potent as x-rays or gamma rays.

Dose is a measure of deposited dose and therefore can never decrease: removal of a radioactive source can reduce only the rate of increase of absorbed dose — never the total absorbed dose.

Biological Effects of Radiation

Ionizing radiation is generally harmful, even potentially lethal, to living organisms.

learning objectives

- Describe effects of ionizing radiation on living organisms.

Example 10.4.2:

The Radium Girls were female factory workers who contracted radiation poisoning from painting watch dials with glow-in-the-dark paint at the United States Radium factory in Orange, New Jersey around 1917. The women, who had been told the paint was harmless, ingested deadly amounts of radium by licking their paintbrushes to give them a fine point; some also painted their fingernails and teeth with the glowing substance.

Ionizing radiation is generally harmful, even potentially lethal, to living organisms. Although radiation was discovered in the late 19th century, the dangers of radioactivity and of radiation were not immediately recognized. The acute effects of radiation were first observed in the use of x-rays when Wilhelm Röntgen intentionally subjected his fingers to x-rays in 1895. The genetic effects of radiation, including the effects on cancer risk, were recognized much later. In 1927, Hermann Joseph Muller published research showing genetic effects.

Some effects of ionizing radiation on human health are stochastic, meaning that their probability of occurrence increases with dose, while the severity is independent of dose. Radiation-induced cancer, teratogenesis, cognitive decline, and heart disease are all examples of stochastic effects. Other conditions, such as radiation burns, acute radiation syndrome, chronic radiation syndrome, and radiation-induced thyroiditis are deterministic, meaning they reliably occur above a threshold dose and their severity increases with dose. Deterministic effects are not necessarily more or less serious than stochastic effects; either can ultimately lead to damage ranging from a temporary nuisance to death.

Radium Girls: Radium dial painters working in a factory

Quantitative data on the effects of ionizing radiation on human health are relatively limited compared to other medical conditions because of the low number of cases to date and because of the stochastic nature of some of the effects. Stochastic effects can only be measured through large epidemiological studies in which enough data have been collected to remove confounding factors such as smoking habits and other lifestyle factors. The richest source of high-quality data is the study of Japanese atomic bomb survivors.

Two pathways of exposure to ionizing radiation exist. In the case of external exposure, the radioactive source is outside (and remains outside) the exposed organism. Examples of external exposure include a nuclear worker whose hands have been dirtied with radioactive dust or a person who places a sealed radioactive source in his pocket. External exposure is relatively easy to estimate, and the irradiated organism does not become radioactive, except if the radiation is an intense neutron beam that causes activation. In the case of internal exposure, the radioactive material enters the organism, and the radioactive atoms become incorporated into the organism. This can occur through inhalation, ingestion, or injection. Examples of internal exposure include potassium-40 present within a normal person or the ingestion of a soluble radioactive substance, such as strontium-89 in cows' milk. When radioactive compounds enter the human body, the effects are different from those resulting from exposure to an external radiation source. Especially in the case of alpha radiation, which normally does not penetrate the skin, the exposure can be much more damaging after ingestion or inhalation.

Therapeutic Uses of Radiation

Radiation therapy uses ionizing radiation to treat conditions such as hyperthyroidism, cancer, and blood disorders.

learning objectives

- Explain difference between external beam radiotherapy and brachytherapy.

Radiation therapy involves the application of ionizing radiation to treat conditions such as hyperthyroidism, thyroid cancer, and blood disorders. Radiation therapy is particularly effective as a treatment of a number of types of cancer if they are localized to one area of the body. It may also be used as part of curative therapy, to prevent tumor recurrence after surgery, or to remove a primary malignant tumor. Radiation therapy is synergistic with chemotherapy and has been used before, during, and after chemotherapy in susceptible cancers.

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External Beam Therapy: Radiation therapy of the pelvis. Lasers and a mold under the legs are used for precise positioning

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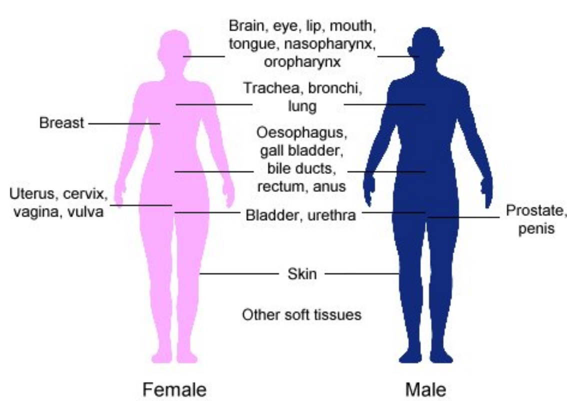


Clinical Applications of Brachytherapy: Body sites in which brachytherapy can be used to treat cancer

Radiation therapy is in itself painless. Many low-dose palliative treatments (for example, radiation therapy targeting bony metastases) cause minimal or no side effects, although short-term pain flare-ups can be experienced in the days following treatment due to edemas compressing nerves in the treated area. Higher doses can cause varying side effects during treatment (acute), in the months or years following treatment (long-term), or after re-treatment (cumulative). The nature, severity, and longevity of side effects depend on the organs that receive the radiation, the treatment itself (type of radiation, dose, fractionation, concurrent chemotherapy), and the individual patient.

Radiation from Food

Food irradiation is a process of treating a food to a specific dosage of ionizing radiation for a predefined length of time.

learning objectives

- Explain how food irradiation is performed, commenting on its purpose and safety

Food irradiation is a process of treating a food to a specific dosage of ionizing radiation for a predefined length of time. This process slows or halts spoilage that is due to the growth of pathogens. Food irradiation is currently permitted by over 50 countries, and the volume of food treated is estimated to exceed 500,000 metric tons annually worldwide. Irradiated food is sold in regular stores, often in specially marked packages .

Radura Logo: The Radura logo, required by U.S. Food and Drug Administration regulations to show a food has been treated with ionizing radiation

By irradiating food, depending on the dose, some or all of the microorganisms, bacteria, viruses, and insects present are killed. This prolongs the shelf-life of the food in cases where pathogenic spoilage is the limiting factor. Some foods, e.g., herbs and spices, are irradiated at sufficient doses (five kilograys or more) to reduce the microbial counts by several orders of magnitude. Such ingredients do not carry spoilage or pathogen microorganisms into the final product. It has also been shown that irradiation can delay the ripening of fruits and the sprouting of vegetables.

Food irradiation using cobalt-60 is the preferred method by most processors. This is because the deep penetration of gamma rays allows for the treatment of entire industrial pallets or totes at once, which reduces the need for material handling. A pallet or tote is typically exposed for several minutes to several hours, depending on the dose. Radioactive material must be monitored and carefully stored to shield workers and the environment from its gamma rays. During operation this is achieved using concrete shields. With most designs the radioisotope can be lowered into a water-filled source storage pool to allow maintenance personnel to enter the radiation shield. In this mode the water in the pool absorbs the radiation.

X-ray irradiators are considered an alternative to isotope-based irradiation systems. X-rays are generated by colliding accelerated electrons with a dense material (the target), such as tantalum or tungsten, in a process known as bremsstrahlung-conversion. X-ray irradiators are scalable and have deep penetration comparable to Co-60, with the added benefit that the electronic source stops radiating when switched off. They also permit dose uniformity, but these systems generally have low energetic efficiency during the conversion of electron energy to photon radiation, so they require much more electrical energy than other systems. X-ray systems also rely on concrete shields to protect the environment and workers from radiation.

Irradiated food does not become radioactive, since the particles that transmit radiation are not themselves radioactive. Still, there is some controversy in the application of irradiation due to its novelty, the association with the nuclear industry, and the potential for the chemical changes to be different than the chemical changes due to heating food (since ionizing radiation produces a higher energy transfer per collision than conventional radiant heat).

Tracers

A radioactive tracer is a chemical compound in which one or more atoms have been replaced by a radioisotope.

learning objectives

- Explain structure and use of radioactive tracers

A radioactive tracer is a chemical compound in which one or more atoms have been replaced by a radioisotope. By virtue of its consequent radioactive decay, this compound can be used to explore the mechanism of chemical reactions by tracing the path that the radioisotope follows from reactants to products.

The underlying principle in the creation of a radioactive tracer is that an atom in a chemical compound is replaced by another atom of the same chemical element. In a tracer, this substituting atom is a radioactive isotope. This process is often called radioactive labeling. Radioactive decay is much more energetic than chemical reactions. Therefore, the radioactive isotope can be present in low concentration and its presence still detected by sensitive radiation detectors such as Geiger counters and scintillation counters.

Geiger Counter: Image of a Geiger counter with pancake-type probe

There are two main ways in which radioactive tracers are used:

When a labeled chemical compound undergoes chemical reactions, one or more of the products will contain the radioactive label. Analysis of what happens to the radioactive isotope provides detailed information about the mechanism of the chemical reaction.
A radioactive compound can be introduced into a living organism. The radio-isotope provides a way to build an image showing how that compound and its reaction products are distributed around the organism.
All the commonly used radioisotopes (Tritium (^{3}H), ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{32}P, ^{35}S, ^{99m}Tc, and ^{123}I) have short half-lives. They do not occur in nature and are produced through nuclear reactions.

Iodine; 123 Radioisotope: Lead container containing iodine-123 radioisotope

Nuclear Fusion

In nuclear fusion two or more atomic nuclei collide at very high speed and join, forming a new nucleus.

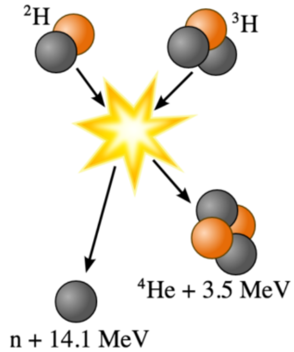
learning objectives

- Analyze possibility of the use of nuclear fusion for the production of electricity.

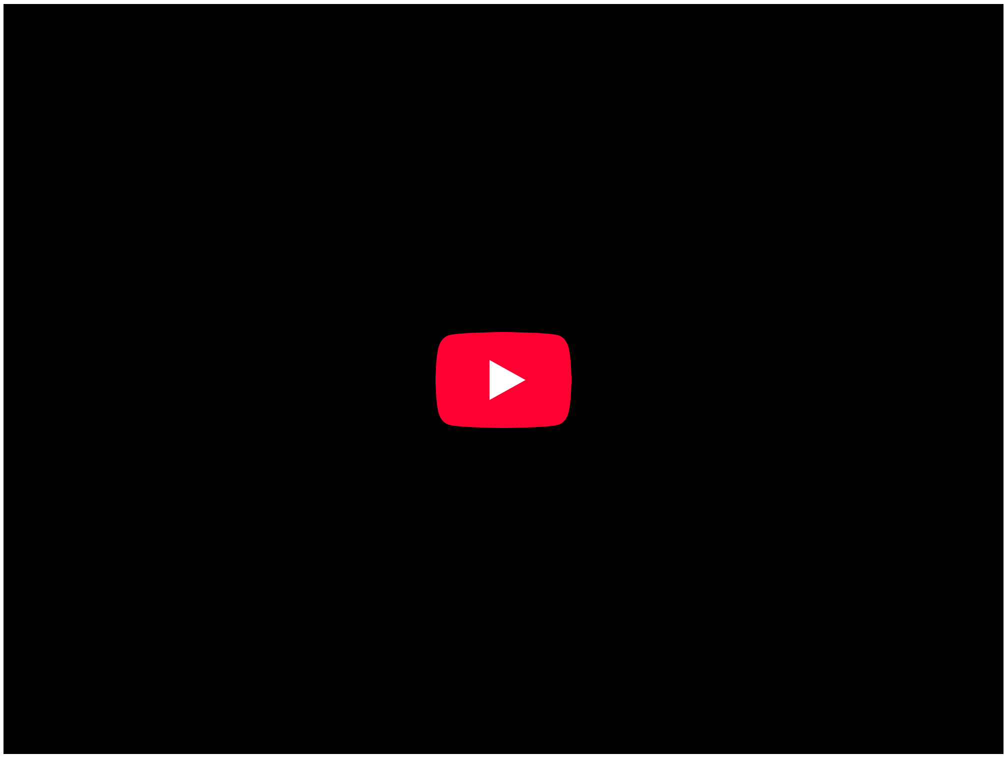
Example 10.4.3:

The sun is a main-sequence star and therefore generates its energy through nuclear fusion of hydrogen nuclei into helium. In its core, the sun fuses 620 million metric tons of hydrogen each second.

Nuclear fusion is a nuclear reaction in which two or more atomic nuclei collide at very high speed and join to form a new type of atomic nucleus. During this process, matter is not conserved because some of the mass of the fusing nuclei is converted into energy.



Fusion of Deuterium with Tritium: Fusion of deuterium with tritium creating helium-4, freeing a neutron, and releasing 17.59 MeV of energy; some mass changes form to appear as the kinetic energy of the products



Fission and Fusion

Describes the difference between fission and fusion

Fusion reactions of light elements power the stars and produce virtually all elements in a process called nucleosynthesis. The fusion of lighter elements in stars releases energy and mass. For example, in the fusion of two hydrogen nuclei to form helium, 0.7 percent of the mass is carried away from the system in the form of kinetic energy or other forms of energy (such as electromagnetic radiation).

It takes considerable energy to force nuclei to fuse, even nuclei of the lightest element, hydrogen. This is because all nuclei have a positive charge due to their protons, and since like charges repel, nuclei strongly resist being put close together. Accelerated to high speeds, they can overcome this electrostatic repulsion and be forced close enough for the attractive nuclear force to be sufficiently strong to achieve fusion. The fusion of lighter nuclei, which creates a heavier nucleus and often a free neutron or proton, generally releases more energy than it takes to force the nuclei together. This is an exothermic process that can produce self-sustaining reactions.

Research into controlled fusion, with the aim of producing fusion power for the production of electricity, has been conducted for over 60 years. It has been accompanied by extreme scientific and technological difficulties, but it has resulted in progress. At present, controlled fusion reactions have been unable to produce self-sustaining controlled fusion reactions. Researchers are working on a reactor that theoretically will deliver 10 times more fusion energy than the amount needed to heat up plasma to required temperatures. Workable designs of this reactor were originally scheduled to be operational in 2018; however, this has been delayed, and a new date has not been released.

Nuclear Fission in Reactors

Nuclear reactors convert the thermal energy released from nuclear fission into electricity.

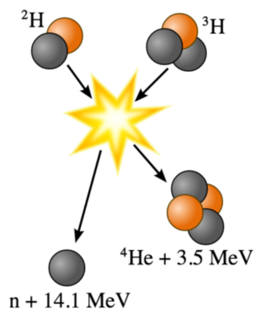
learning objectives

- Explain how nuclear chain reactions can be controlled.

Example 10.4.4:

Some serious nuclear and radiation accidents have occurred. In 2011, three of the reactors at Fukushima I overheated, causing meltdowns that eventually led to explosions, which released large amounts of radioactive material into the air.

Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller (lighter) nuclei. This reaction often produces free neutrons and photons (in the form of gamma rays) and releases a very large amount of energy, even by the standards of radioactive decay . The two nuclei produced are most often of comparable but slightly different sizes, typically with a mass ratio of products of about 3 to 2, for common fissile nuclides.



Nuclear Fission Reaction: An induced nuclear fission event. A neutron is absorbed by the nucleus of a uranium-235 atom, which in turn splits into fast-moving lighter elements (fission products) and free neutrons

For example, when a large fissile atomic nucleus such as uranium-235 or plutonium-239 absorbs a neutron, it may undergo nuclear fission. The heavy nucleus splits into two or more lighter nuclei (the fission products), releasing kinetic energy, gamma radiation, and free neutrons. A portion of these neutrons may later be absorbed by other fissile atoms and trigger further fission events, which release more neutrons, and so on. This is known as a nuclear chain reaction.

Just as conventional power stations generate electricity by harnessing the thermal energy released from burning fossil fuels, the thermal energy released from nuclear fission can be converted in electricity by nuclear reactors. A nuclear chain reaction can be controlled by using neutron poisons and neutron moderators to change the percentage of neutrons that will go on to cause more fissions. Nuclear reactors generally have automatic and manual systems to shut the fission reaction down if unsafe conditions are detected.

The reactor core generates heat in a number of ways. The kinetic energy of fission products is converted to thermal energy when these nuclei collide with nearby atoms. Some of the gamma rays produced during fission are absorbed by the reactor, and their energy is converted to heat. Heat is produced by the radioactive decay of fission products and materials that have been activated by neutron absorption. This decay heat source will remain for some time even after the reactor is shut down.

A nuclear reactor coolant — usually water, but sometimes a gas, liquid metal, or molten salt — is circulated past the reactor core to absorb the heat that it generates. The heat is carried away from the reactor and is then used to generate steam.

The power output of the reactor is adjusted by controlling how many neutrons are able to create more fissions. Control rods that are made of a neutron poison are used to absorb neutrons. Absorbing more neutrons in a control rod means that there are fewer neutrons available to cause fission, so pushing the control rod deeper into the reactor will reduce the reactor's power output, and extracting the control rod will increase it.

Control Rod Assembly: Control rod assembly, above fuel element

Some serious nuclear and radiation accidents have occurred. Nuclear power plant accidents include the Chernobyl disaster (1986), the Fukushima Daiichi nuclear disaster (2011), the Three Mile Island accident (1979), and the SL-1 accident (1961).

Nuclear safety involves the actions taken to prevent nuclear and radiation accidents or to limit their consequences. The nuclear power industry has improved the safety and performance of reactors and has proposed new safer (but generally untested) reactor designs. However, there is no guarantee that these reactors will be designed, built, and operated correctly.

Fukushima Daiichi Nuclear Disaster: Satellite image taken March 16, 2011 of the four damaged reactor buildings

Emission Topography

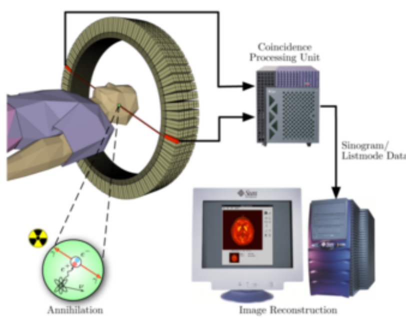
Positron emission tomography is a nuclear medical imaging technique that produces a three-dimensional image of processes in the body.

learning objectives

- Discuss possibility of uses of positron emission tomography with other diagnostic techniques.

Positron emission tomography (PET) is a nuclear medical imaging technique that produces a three-dimensional image or picture of functional processes in the body. The system detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule. Three-dimensional images of tracer concentration within the body are then constructed by computer analysis.

PET acquisition process occurs as the radioisotope undergoes positron emission decay (also known as positive beta decay), it emits a positron, an antiparticle of the electron with opposite charge. The emitted positron travels in tissue for a short distance (typically less than 1 mm, but dependent on the isotope), during which time it loses kinetic energy, until it decelerates to a point where it can interact with an electron. The encounter annihilates both electron and positron, producing a pair of annihilation (gamma) photons moving in approximately opposite directions. These are detected when they reach a scintillator in the scanning device, creating a burst of light which is detected by photomultiplier tubes or silicon avalanche photodiodes . The technique depends on simultaneous or coincident detection of the pair of photons moving in approximately opposite directions (it would be exactly opposite in their center of mass frame, but the scanner has no way to know this, and so has a built-in slight direction-error tolerance). Photons that do not arrive in temporal “pairs” (i.e. within a timing-window of a few nanoseconds) are ignored.



Positron Emission Tomography Acquisition Process: Schema of a PET acquisition process.

A technique much like the reconstruction of computed tomography (CT) and single-photon emission computed tomography (SPECT) data is more commonly used, although the data set collected in PET is much poorer than CT, so reconstruction techniques are more difficult.

PET scans are increasingly read alongside CT or magnetic resonance imaging (MRI) scans, with the combination giving both anatomic and metabolic information. Because PET imaging is most useful in combination with anatomical imaging, such as CT, modern PET scanners are now available with integrated high-end multi-detector-row CT scanners . Because the two scans can be performed in immediate sequence during the same session, with the patient not changing position between the two types of scans, the two sets of images are more-precisely registered, so that areas of abnormality on the PET imaging can be more perfectly correlated with anatomy on the CT images. This is very useful in showing detailed views of moving organs or structures with higher anatomical variation, which is more common outside the brain.

PET/CT-System: PET/CT-System with 16-slice CT; the ceiling mounted device is an injection pump for CT contrast agent.

PET scanning is non-invasive, but it does involve exposure to ionizing radiation. The total dose of radiation is significant, usually around 5–7 mSv. However, in modern practice, a combined PET/CT scan is almost always performed, and for PET/CT scanning, the radiation exposure may be substantial—around 23–26 mSv (for a 70 kg person—dose is likely to be higher for higher body weights). When compared to the classification level for radiation workers in the UK of 6 mSv, it can be seen that use of a PET scan needs proper justification.

Nuclear Weapons

A nuclear weapon is an explosive device that derives its destructive force from nuclear reactions—either fission, fusion, or a combination.

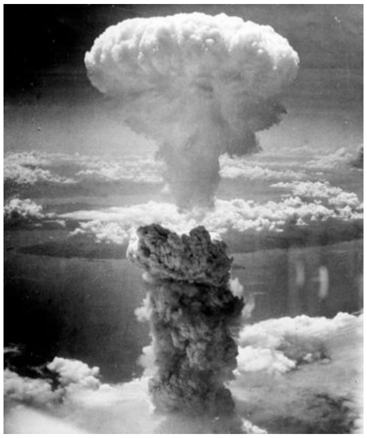
learning objectives

- Explain the difference between an "atomic" bomb and a "hydrogen" bomb, discussing their history

A nuclear weapon is an explosive device that derives its destructive force from nuclear reactions, either fission or a combination of fission and fusion. Both reactions release vast quantities of energy from relatively small amounts of matter. The first fission (i.e., "atomic") bomb test released the same amount of energy as approximately 20,000 tons of trinitrotoluene (TNT). The first fusion (i.e., thermonuclear "hydrogen") bomb test released the same amount of energy as approximately 10,000,000 tons of TNT.

A modern thermonuclear weapon weighing little more than 2,400 pounds (1,100 kg) can produce an explosive force comparable to the detonation of more than 1.2 million tons (1.1 million tonnes) of TNT. Thus, even a small nuclear device no larger than traditional bombs can devastate an entire city by blast, fire and radiation. Nuclear weapons are considered weapons of mass destruction, and their use and control have been a major focus of international relations policy since their inception.

Only two nuclear weapons have been used in the course of warfare, both by the United States near the end of World War II. On August 6, 1945, a uranium gun-type fission bomb code-named "Little Boy" was detonated over the Japanese city of Hiroshima. Only three days later a plutonium implosion-type fission bomb code-named "Fat Man" (as illustrated in) was exploded over Nagasaki, Japan. The resulting mushroom cloud is shown in . The death toll from the two bombings was estimated at approximately 200,000 people—mostly civilians, and mainly from acute injuries sustained from the explosions. The role of the bombings in Japan's surrender, and their ethical implications, remain the subject of scholarly and popular debate.



Nagasaki Atomic Bombing: The mushroom cloud of the atomic bombing of Nagasaki, Japan (August 9,1945) rose some 18 kilometers (11 mi) above the bomb's hypocenter.

Fat Man Atomic Bomb: The first nuclear weapons were gravity bombs, such as this "Fat Man" weapon dropped on Nagasaki, Japan. They were very large and could only be delivered by heavy bomber aircraft.

Since the bombings of Hiroshima and Nagasaki, nuclear weapons have been detonated on over two thousand occasions for testing purposes and demonstrations. Only a small number of nations either possess such weapons, or are suspected of trying to acquire and/or develop them. The only countries known to have detonated nuclear weapons (and that acknowledge possessing such weapons) are, as listed chronologically by date of first test: the United States, the Soviet Union (succeeded as a nuclear power by Russia), the United Kingdom, France, the People's Republic of China, India, Pakistan, and North Korea. In addition, it is also widely believed that Israel possesses nuclear weapons (though they have not admitted to it).

The Federation of American Scientists estimates that as of 2012, there are more than 17,000 nuclear warheads in the world, with around 4,300 considered "operational"—as in ready for use.

NMR and MRIs

Magnetic resonance imaging is a medical imaging technique used in radiology to visualize internal structures of the body in detail.

learning objectives

- Explain the difference between magnetic resonance imaging and computed tomography.

Magnetic resonance imaging (MRI), also called nuclear magnetic resonance imaging (NMRI) or magnetic resonance tomography (MRT), is a medical imaging technique used in radiology to visualize internal structures of the body in detail. MRI utilized the property of nuclear magnetic resonance (NMR) to image the nuclei of atoms inside the body.

MRI machines (as pictured in) make use of the fact that body tissue contains a large amount of water and therefore protons (1H nuclei), which get aligned in a large magnetic field. Each water molecule has two hydrogen nuclei or protons. When a person is inside the scanner's powerful magnetic field, the hydrogen protons in their body align with the direction of the field. A radio frequency current is briefly activated, producing a varying electromagnetic field. This electromagnetic field has just the right frequency (known as the resonance frequency) to become absorbed and then reverse the rotation of the hydrogen protons in the magnetic field.

MRI Scanner: Phillips MRI scanner in Gothenburg, Sweden.

After the electromagnetic field is turned off, the rotations of the hydrogen protons return to thermodynamic equilibrium, and then realign with the static magnetic field. During this relaxation, a radio frequency signal (electromagnetic radiation in the RF range) is generated; this signal can be measured with receiver coils. Hydrogen protons in different tissues return to their equilibrium state at different relaxation rates. Images are then constructed by performing a complex mathematical analysis of the signals emitted by the hydrogen protons.

MRI shows a marked contrast between the different soft tissues of the body, making it especially useful in imaging the brain, the muscles, the heart, and cancerous tissue—as compared with other medical imaging techniques such as computed tomography (CT) or X-rays. MRI contrast agents may be injected intravenously to enhance the appearance of blood vessels, tumors or inflammation.

Unlike CT, MRI does not use ionizing radiation and is generally a very safe procedure. The strong magnetic fields and radio pulses can, however, affect metal implants (including cochlear implants and cardiac pacemakers).

Key Points

- Ionizing radiation works by damaging the DNA of exposed tissue, leading to cellular death.
- In external beam radiotherapy, shaped radiation beams are aimed from several angles of exposure to intersect at the tumor, providing a much larger absorbed dose there than in the surrounding, healthy tissue.
- In brachytherapy, a therapeutic radioisotope is injected into the body to chemically localize to the tissue that requires destruction.
- There are several ways of measuring doses of ionizing radiation: personal dosimeters, ionization chambers, and internal dosimetry.
- The distinction between absorbed dose (Gy/rad) and dose equivalent (Sv/rem) is based upon the biological effects.
- Dose is a measure of deposited dose and therefore can never decrease: removal of a radioactive source can reduce only the rate of increase of absorbed dose — never the total absorbed dose.
- The effects of ionizing radiation on human health are separated into stochastic effects (the probability of occurrence increases with dose) and deterministic effects (they reliably occur above a threshold dose, and their severity increases with dose).
- Quantitative data on the effects of ionizing radiation on human health are relatively limited compared to other medical conditions because of the low number of cases to date and because of the stochastic nature of some of the effects.
- Two pathways (external and internal) of exposure to ionizing radiation exist.
- Ionizing radiation works by damaging the DNA of exposed tissue, leading to cellular death.
- In external beam radiotherapy, shaped radiation beams are aimed from several angles of exposure to intersect at the tumor, providing a much larger absorbed dose there than in the surrounding, healthy tissue.
- In brachytherapy, a therapeutic radioisotope is injected into the body to chemically localize to the tissue that requires destruction.
- Food irradiation kills some of the microorganisms, bacteria, viruses, and insects found in food. It prolongs shelf-life in cases where pathogenic spoilage is the limiting factor.
- Food irradiation using cobalt-60 is the preferred method by most processors.
- Irradiated food does not become radioactive, since the particles that transmit radiation are not themselves radioactive.
- Radioactive tracers are used to explore the mechanism of chemical reactions by tracing the path that the radioisotope follows from reactants to products.
- The radioactive isotope can be present in low concentration and its presence still detected by sensitive radiation detectors.
- All the commonly used radioisotopes have short half-lives, do not occur in nature, and are produced through nuclear reactions.
- The fusion of lighter elements releases energy.
- Matter is not conserved during fusion reactions.
- Fusion reactions power the stars and produce virtually all elements in a process called nucleosynthesis.
- Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, releasing a very large amount of energy.
- Nuclear chain reactions can be controlled using neutron poisons and neutron moderators.
- Although the nuclear power industry has improved the safety and performance of reactors and has proposed new, safer reactor designs, there is no guarantee that serious nuclear accidents will not occur.
- PET scanning utilizes detection of gamma rays emitted indirectly by a positron-emitting radionuclide (tracer), which is introduced into the body on a biologically active molecule.
- PET scans are increasingly read alongside CT or magnetic resonance imaging (MRI) scans, with the combination giving both anatomic and metabolic information.
- PET scanning is non-invasive, but it does involve exposure to ionizing radiation.
- Nuclear weapons utilize either fission (“atomic” bomb) or combination of fission and fusion (“hydrogen” bomb).

- Nuclear weapons are considered weapons of mass destruction.
- The use and control of nuclear weapons is a major focus of international relations policy since their first use.
- MRI makes use of the property of nuclear magnetic resonance to image nuclei of atoms inside the body.
- MRI provides good contrast between the different soft tissues of the body (making it especially useful in imaging the brain, the muscles, the heart, and cancerous tissue).
- Although MRI uses non-ionizing radiation, the strong magnetic fields and radio pulses can affect metal implants, including cochlear implants and cardiac pacemakers.

Key Terms

- **external beam therapy**: Radiotherapy that directs the radiation at the tumour from outside the body.
- **ionizing radiation**: high-energy radiation that is capable of causing ionization in substances through which it passes; also includes high-energy particles
- **brachytherapy**: Radiotherapy using radioactive sources positioned within (or close to) the treatment volume.
- **diode**: an electronic device that allows current to flow in one direction only; a valve
- **dosimeter**: A dosimeter is a device used to measure a dose of ionizing radiation. These normally take the form of either optically stimulated luminescence (OSL), photographic-film, thermoluminescent (TLD), or electronic personal dosimeters (PDM).
- **gamma ray**: A very high frequency (and therefore very high energy) electromagnetic radiation emitted as a consequence of radioactivity.
- **x-ray**: Short-wavelength electromagnetic radiation usually produced by bombarding a metal target in a vacuum. Used to create images of the internal structure of objects; this is possible because x-rays pass through most objects and can expose photographic film
- **radioactive tracer**: a radioactive isotope that, when injected into a chemically similar substance, or artificially attached to a biological or physical system, can be traced by radiation detection devices
- **isotope**: any of two or more forms of an element where the atoms have the same number of protons but a different number of neutrons within their nuclei. As a consequence, atoms for the same isotope will have the same atomic number but different mass numbers (atomic weights)
- **radioactive decay**: any of several processes by which unstable nuclei emit subatomic particles and/or ionizing radiation and disintegrate into one or more smaller nuclei
- **nucleosynthesis**: any of several processes that lead to the synthesis of heavier atomic nuclei
- **fusion**: A nuclear reaction in which nuclei combine to form more massive nuclei with the concomitant release of energy.
- **control rod**: any of a number of steel tubes, containing boron or another neutron absorber, that is inserted into the core of a nuclear reactor in order to control its rate of reaction
- **nuclear reactor**: any device in which a controlled chain reaction is maintained for the purpose of creating heat (for power generation) or for creating neutrons and other fission products for experimental, medical, or other purposes
- **fission**: The process of splitting the nucleus of an atom into smaller particles; nuclear fission.
- **tracer**: A chemical used to track the progress or history of a natural process.
- **positron**: The antimatter equivalent of an electron, having the same mass but a positive charge.
- **tomography**: Imaging by sections or sectioning.
- **warfare**: The waging of war or armed conflict against an enemy.
- **computed tomography**: (CT) – A form of radiography which uses computer software to create images, or slices, at various planes of depth from images taken around a body or volume of interest.
- **nuclear magnetic resonance**: (NMRI) – The absorption of electromagnetic radiation (radio waves), at a specific frequency, by an atomic nucleus placed in a strong magnetic field; used in spectroscopy and in magnetic resonance imaging.
- **magnetic resonance imaging**: Commonly referred to as MRI; a technique that uses nuclear magnetic resonance to form cross sectional images of the human body for diagnostic purposes.

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