1: THE BASICS OF PHYSICS

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CHAPTER OVERVIEW

1: The Basics of Physics

Topic hierarchy

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1.2: Units

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1.1: The Basics of Physics

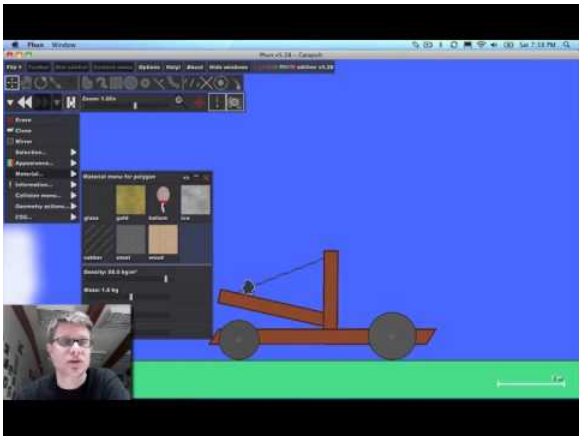
Introduction: Physics and Matter

Physics is a study of how the universe behaves.

learning objectives

- Apply physics to describe the function of daily life

Physics is a natural science that involves the study of matter and its motion through space and time, along with related concepts such as energy and force. More broadly, it is the study of nature in an attempt to understand how the universe behaves.



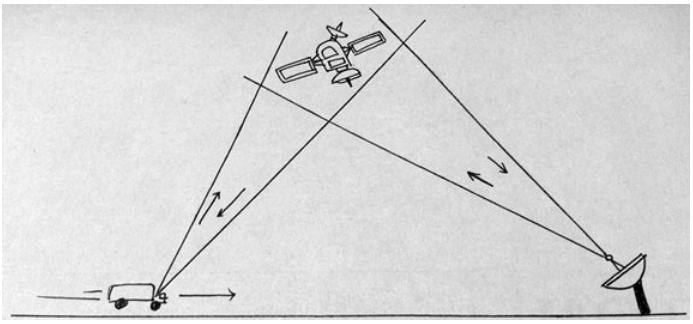
What is Physics?: Mr. Andersen explains the importance of physics as a science. History and virtual examples are used to give the discipline context.

Physics uses the scientific method to help uncover the basic principles governing light and matter, and to discover the implications of those laws. It assumes that there are rules by which the universe functions, and that those laws can be at least partially

understood by humans. It is also commonly believed that those laws could be used to predict everything about the universe's future if complete information was available about the present state of all light and matter.

Matter is generally considered to be anything that has mass and volume. Many concepts integral to the study of classical physics involve theories and laws that explain matter and its motion. The law of conservation of mass, for example, states that mass cannot be created or destroyed. Further experiments and calculations in physics, therefore, take this law into account when formulating hypotheses to try to explain natural phenomena.

Physics aims to describe the function of everything around us, from the movement of tiny charged particles to the motion of people, cars, and spaceships. In fact, almost everything around you can be described quite accurately by the laws of physics. Consider a smart phone; physics describes how electricity interacts with the various circuits inside the device. This knowledge helps engineers select the appropriate materials and circuit layout when building the smart phone. Next, consider a GPS system; physics describes the relationship between the speed of an object, the distance over which it travels, and the time it takes to travel that distance. When you use a GPS device in a vehicle, it utilizes these physics equations to determine the travel time from one location to another. The study of physics is capable of making significant contributions through advances in new technologies that arise from theoretical breakthroughs.



Global Positioning System: GPS calculates the speed of an object, the distance over which it travels, and the time it takes to travel that distance using equations based on the laws of physics.

Physics and Other Fields

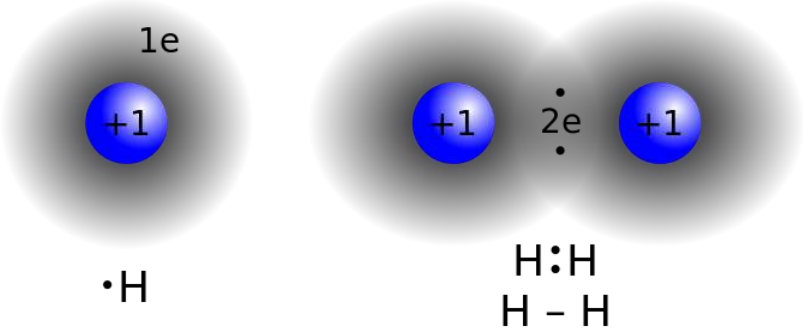
Physics is the foundation of many disciplines and contributes directly to chemistry, astronomy, engineering, and most scientific fields.

learning objectives

- Explain why the study of physics is integral to the study of other sciences

Physics and Other Disciplines

Physics is the foundation of many important disciplines and contributes directly to others. Chemistry deals with the interactions of atoms and molecules, so it is rooted in atomic and molecular physics. Most branches of engineering are applied physics. In architecture, physics is at the heart of structural stability and is involved in acoustics, heating, lighting, and the cooling of buildings. Parts of geology rely heavily on physics, such as the radioactive dating of rocks, earthquake analysis, and heat transfer in the Earth. Some disciplines, such as biophysics and geophysics, are hybrids of physics and other disciplines.



Physics in Chemistry: The study of matter and electricity in physics is fundamental towards the understanding of concepts in chemistry, such as the covalent bond.

Physics has many applications in the biological sciences. On the microscopic level, it helps describe the properties of cell walls and cell membranes. On the macroscopic level, it can explain the heat, work, and power associated with the human body. Physics is involved in medical diagnostics, such as X-rays, magnetic resonance imaging (MRI), and ultrasonic blood flow measurements. Medical therapy sometimes directly involves physics: cancer radiotherapy uses ionizing radiation, for instance. Physics can also explain sensory phenomena, such as how musical instruments make sound, how the eye detects color, and how lasers can transmit information.

The boundary between physics and the other sciences is not always clear. For instance, chemists study atoms and molecules, which are what matter is built from, and there are some scientists who would be equally willing to call themselves physical chemists or chemical physicists. It might seem that the distinction between physics and biology would be clearer, since physics seems to deal with inanimate objects. In fact, almost all physicists would agree that the basic laws of physics that apply to molecules in a test tube work equally well for the combination of molecules that constitutes a bacterium. What differentiates physics from biology is that many of the scientific theories that describe living things ultimately result from the fundamental laws of physics, but cannot be rigorously derived from physical principles.

It is not necessary to formally study all applications of physics. What is most useful is the knowledge of the basic laws of physics and skill in the analytical methods for applying them. The study of physics can also improve your problem-solving skills. Furthermore, physics has retained the most basic aspects of science, so it is used by all of the sciences. The study of physics makes other sciences easier to understand.

Models, Theories, and Laws

The terms *model*, *theory*, and *law* have exact meanings in relation to their usage in the study of physics.

learning objectives

- Define the terms model, theory, and law

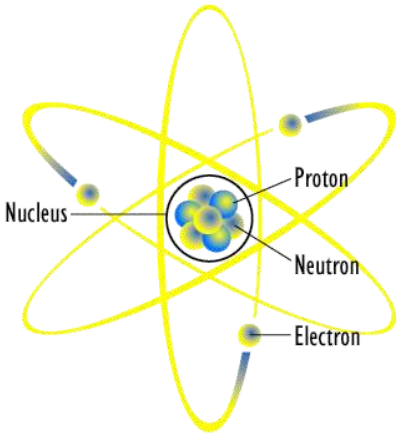
Definition of Terms: Model, Theory, Law

In colloquial usage, the terms *model*, *theory*, and *law* are often used interchangeably or have different interpretations than they do in the sciences. In relation to the study of physics, however, each term has its own specific meaning.

The *laws of nature* are concise descriptions of the universe around us. They are not explanations, but human statements of the underlying rules that all natural processes follow. They are intrinsic to the universe; humans did not create them and we cannot change them. We can only discover and understand them. The cornerstone of discovering natural laws is observation; science must describe the universe as it is, not as we may imagine it to be. Laws can never be known with absolute certainty, because it is impossible to perform experiments to establish and confirm a law in every possible scenario without exception. Physicists operate under the assumption that all scientific laws and theories are valid until a counterexample is observed. If a good-quality, verifiable experiment contradicts a well-established law, then the law must be modified or overthrown completely.

Models

A *model* is a representation of something that is often too difficult (or impossible) to display directly. While a model's design is justified using experimental information, it is only accurate under limited situations. An example is the commonly used "planetary model" of the atom, in which electrons are pictured as orbiting the nucleus, analogous to the way planets orbit the Sun. We cannot observe electron orbits directly, but the mental image helps explain the observations we can make, such as the emission of light from hot gases. Physicists use models for a variety of purposes. For example, models can help physicists analyze a scenario and perform a calculation, or they can be used to represent a situation in the form of a computer simulation.



Planetary Model of an Atom: The planetary model of the atom in which electrons are pictured as orbiting the nucleus, analogous to the way planets orbit the Sun

Theories

A *theory* is an explanation for patterns in nature that is supported by scientific evidence and verified multiple times by various groups of researchers. *Some theories include models to help visualize phenomena, whereas others do not*. Newton's theory of gravity, for example, does not require a model or mental image, because we can observe the objects directly with our own senses. The kinetic theory of gases, on the other hand, makes use of a model in which a gas is viewed as being composed of atoms and molecules. Atoms and molecules are too small to be observed directly with our senses—thus, we picture them mentally to understand what our instruments tell us about the behavior of gases.

Laws

A law uses concise language to describe a generalized pattern in nature that is supported by scientific evidence and repeated experiments. Often, a law can be expressed in the form of a single mathematical equation. Laws and theories are similar in that they are both scientific statements that result from a tested hypothesis and are supported by scientific evidence. However, the designation law is reserved for a concise and very general statement that describes phenomena in nature, such as the law that energy is conserved during any process, or Newton's second law of motion, which relates force, mass, and acceleration by the simple equation $\boldsymbol{F = ma}$. A theory, in contrast, is a less concise statement of observed phenomena. For example, the Theory of Evolution and the Theory of Relativity cannot be expressed concisely enough to be considered a law. The biggest difference between a law and a theory is that a law is much more complex and dynamic, and a theory is more explanatory. A law describes a single observable point of fact, whereas a theory explains an entire group of related phenomena. And, whereas a law is a postulate that forms the foundation of the scientific method, a theory is the end result of that process.

Key Points

- Physics is a natural science that involves the study of matter and its motion through space and time, along with related concepts such as energy and force.
- Matter is generally considered to be anything that has mass and volume.
- Scientific laws and theories express the general truths of nature and the body of knowledge they encompass. These laws of nature are rules that all natural processes appear to follow.

- Many scientific disciplines, such as biophysics, are hybrids of physics and other sciences.
- The study of physics encompasses all forms of matter and its motion in space and time.
- The application of physics is fundamental towards significant contributions in new technologies that arise from theoretical breakthroughs.
- Concepts in physics cannot be proven, they can only be supported or disproven through observation and experimentation.
- A model is an evidence-based representation of something that is either too difficult or impossible to display directly.
- A theory is an explanation for patterns in nature that is supported by scientific evidence and verified multiple times by various groups of researchers.
- A law uses concise language, often expressed as a mathematical equation, to describe a generalized pattern in nature that is supported by scientific evidence and repeated experiments.

Key Terms

- **matter**: The basic structural component of the universe. Matter usually has mass and volume.
- **scientific method**: A method of discovering knowledge about the natural world based in making falsifiable predictions (hypotheses), testing them empirically, and developing peer-reviewed theories that best explain the known data.
- **application**: the act of putting something into operation
- **Model**: A representation of something difficult or impossible to display directly
- **Law**: A concise description, usually in the form of a mathematical equation, used to describe a pattern in nature
- **theory**: An explanation for patterns in nature that is supported by scientific evidence and verified multiple times by various groups of researchers

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1.2: Units

Length

Length is a physical measurement of distance that is fundamentally measured in the SI unit of a meter.

learning objectives

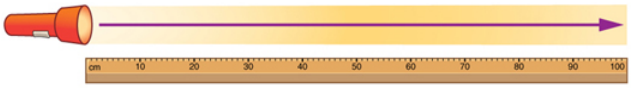
- Distinguish SI and customary units of length

Length can be defined as a measurement of the physical quantity of distance. Many qualitative observations fundamental to physics are commonly described using the measurement of length. The distance between objects, the rate at which objects are traveling, and how much force an object exerts are all dependent on length as a variable. In order to describe length in a standardized and quantitative manner, an accepted unit of measurement must be utilized.

Many different units of length are used around the world. In the United States, the U.S. customary units operationally describe length in terms of the basic unit of an inch. Varying lengths are thus described in relation to the inch, such as a foot equaling 12 inches, a yard equaling three feet, and a mile equaling 1,760 yards.

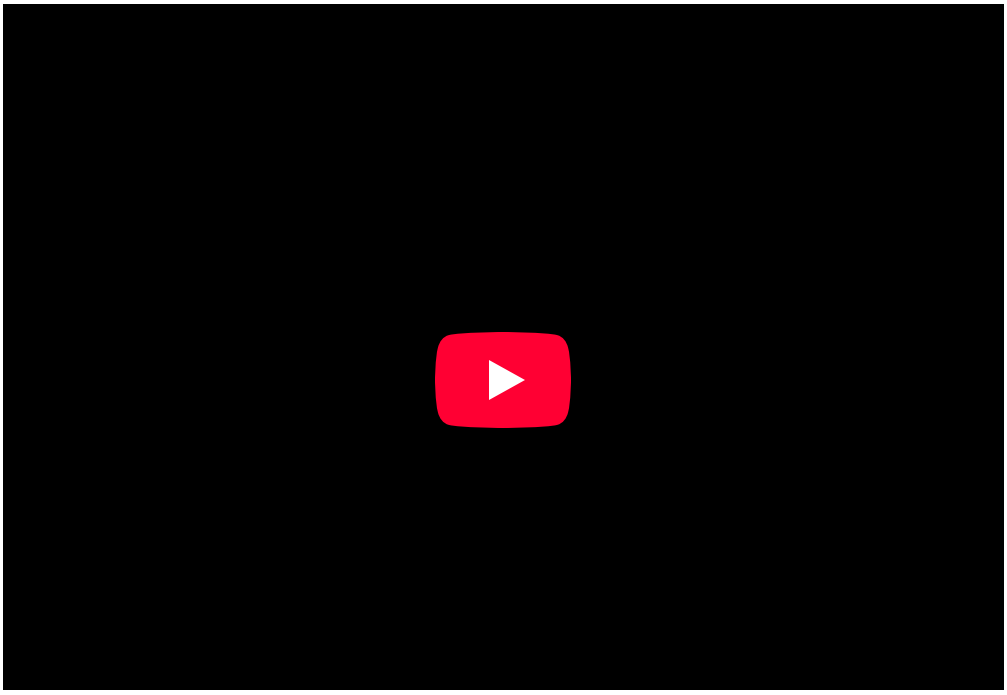
Though regional use of different measurement units is not generally problematic, it can raise issues of compatibility and understanding when working abroad or collaboratively with international partners. As such, a standard unit of measurement that is internationally accepted is needed. The basic unit of length as identified by the International System of Units (SI) is the meter. The meter is expressed more specifically in terms of speed of light.

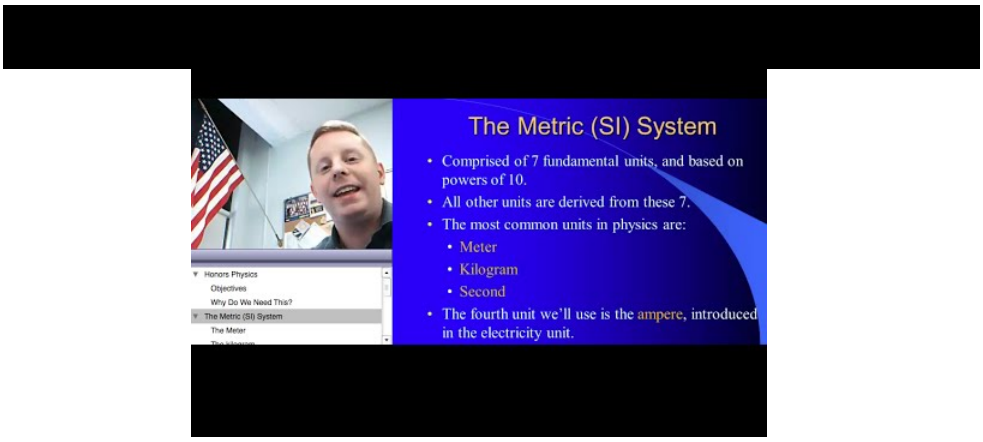
One meter is defined as the distance that light travels in a vacuum in $\frac{1}{299,792,458}$ of a second. All lengths are measured in terms related to the meter, where its multiples are devised around the convenience of the number 10. For example, a centimeter is equal to $\frac{1}{100}$ of a meter (or 10^{-2} meters), and a kilometer is equal to 1,000 meters (or 10^{3} meters).



Light travels a distance of 1 meter
in 1/299,792,458 seconds

Meter Defined by Speed of Light: The meter is defined to be the distance that light travels in $\frac{1}{299,792,458}$ of a second in a vacuum. Distance traveled is speed multiplied by time.





Metric System – Length: A brief introduction to the metric system and unit conversions.

Mass

Mass is the quantity of matter that an object contains, as measured by its resistance to acceleration.

learning objectives

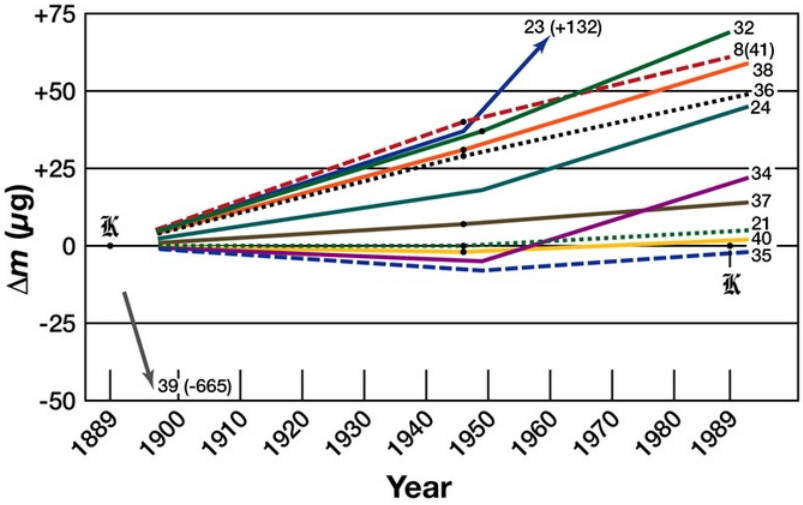
- Explain the difference between mass and weight

Mass

Mass, specifically inertial mass, is a quantitative measure of an object's resistance to acceleration. It is an intrinsic property of an object and does not change because of the environment. The SI unit of mass is the kilogram (kg).

The kilogram is defined as being equal to the mass of the International Prototype Kilogram (IPK), which is almost exactly equal to the mass of one liter of water. It is also the only SI unit that is directly defined by an artifact, rather than a fundamental physical property that can be reproduced in different laboratories. Four of the seven base units in the SI system are defined relative to the kilogram, so the stability of this measurement is crucial for accurate and consistent measurements.

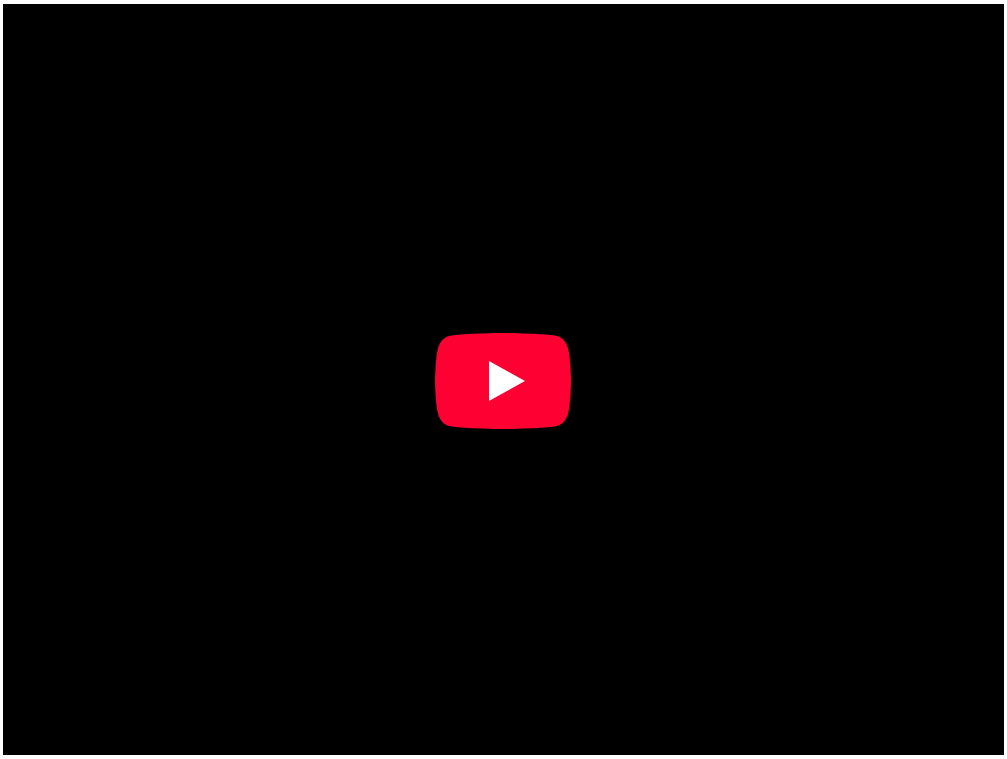
In 2005, the International Committee for Weights and Measures (CIPM) recommended that the kilogram be redefined in terms of a fundamental constant of nature, due to evidence that the International Prototype Kilogram will vary in mass over time. At its 2011 meeting, the General Conference on Weights and Measures (CGPM) agreed that the kilogram should be redefined in terms of the Planck constant. The conference deferred a final decision until its next meeting in 2014.

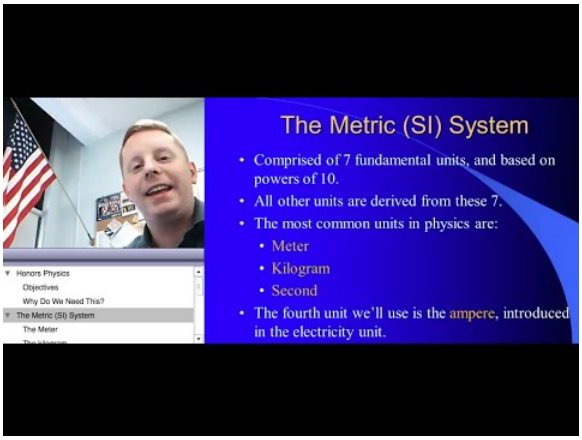


Prototype Mass Drifts: A graph of the relative change in mass of selected kilogram prototypes.

Mass and Weight

In everyday usage, the mass of an object in kilograms is often referred to as its weight. This value, though given in kilograms, is actually the non-SI unit of measure known as the kilogram- force. In scientific terms, ‘weight’ refers to the gravitational force acting on a given body. This measurement changes depending on the gravitational pull of the opposing body. For example, a person’s weight on the Earth is different than a person’s weight on the moon because of the differences in the gravitational pull of each body. In contrast, the mass of an object is an intrinsic property and remains the same regardless of gravitational fields. Accordingly, astronauts in microgravity must exert 10 times more force to accelerate a 10-kg object at the same rate as a 1-kg object, even though the differences in weight are imperceptible.





Metric System – Mass: A brief introduction to the metric system and unit conversions.

Time

Time is the fundamental physical quantity of duration and is measured by the SI Unit known as the second.

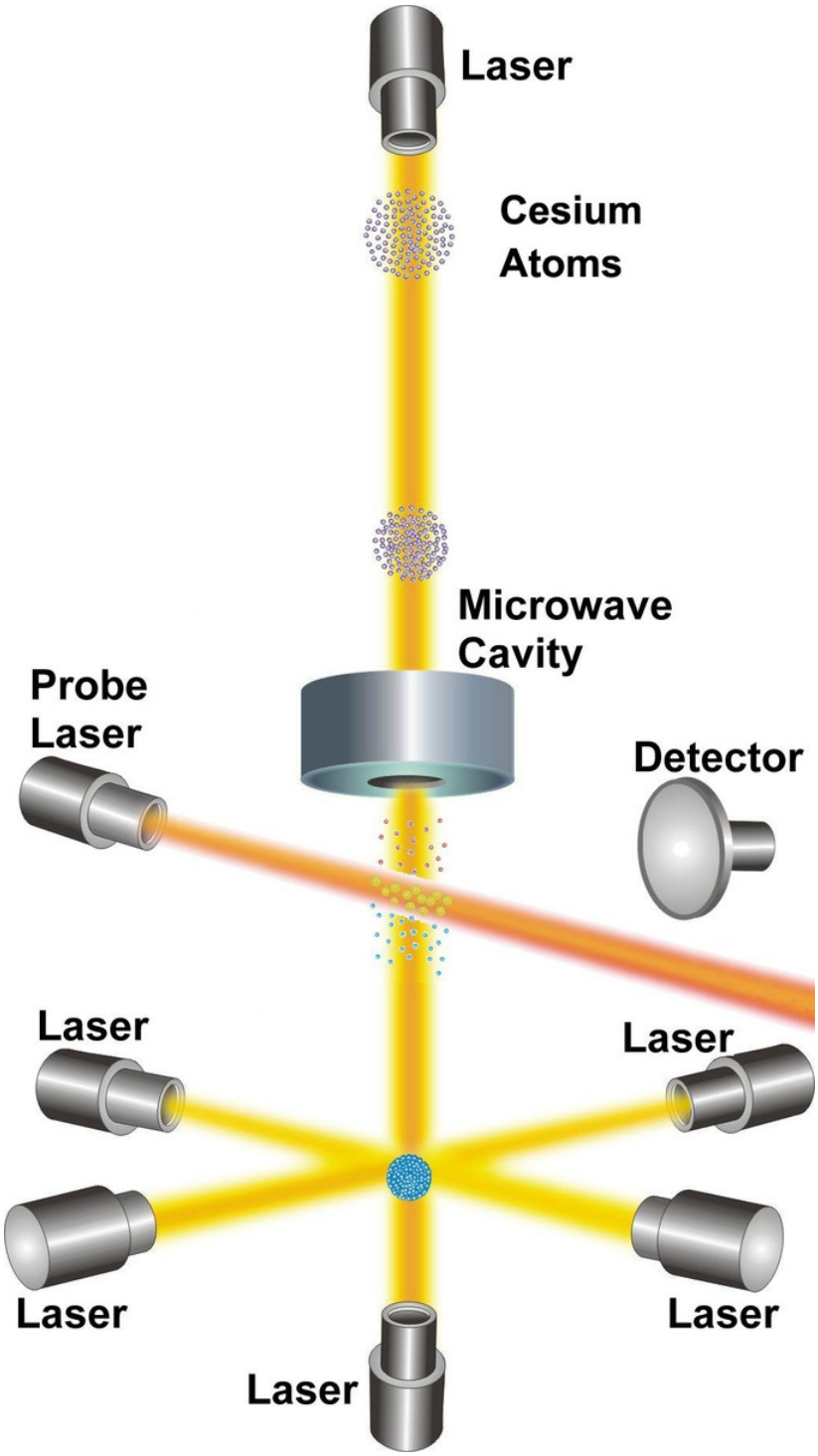
learning objectives

- Relate time with other physical quantities

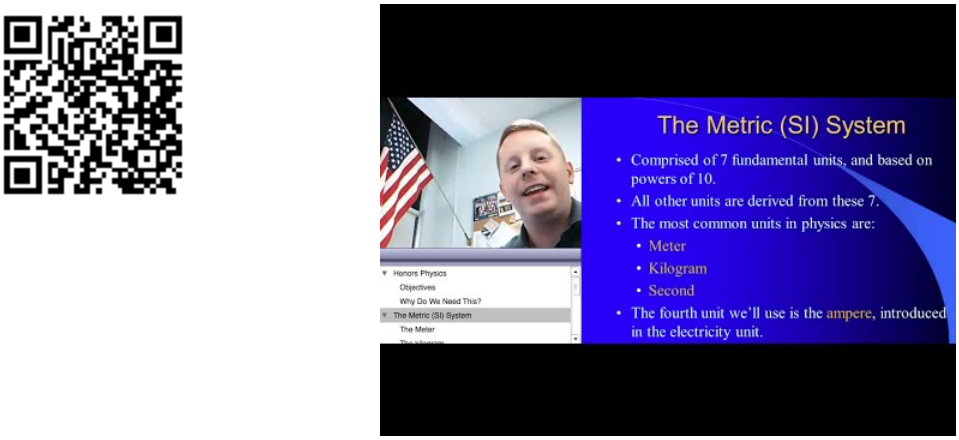
Time is one of the seven fundamental physical quantities in the International System (SI) of Units. Time is used to define other quantities, such as velocity or acceleration, and as such, it is important that it be standardized and quantified precisely. An operational definition of time is highly useful in the conduct of both advanced experiments and everyday affairs of life.

Historically, temporal measurement was a prime motivation in navigation and astronomy. Periodic events and motion have long served as standards for units of time. For example, the movement of the sun across the sky, the phases of the moon, the swing of a pendulum, and the beat of a heart have all been used as a standard for time keeping. These events and standards, however, are highly dynamic in nature and cannot reliably be utilized for accurate quantitative measures. Between 1000 and 1960 the second was defined as $\frac{1}{86,400}$ of a mean solar day. This definition changed between 1960 and 1967 and was defined in terms of the period of the Earth's orbit around the Sun in 1900. Today, the SI Unit of the second is defined in terms of radiation emitted by cesium atoms.

The second is now operationally defined as "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom." It follows that the hyperfine splitting in the ground state of the cesium 133 atom is exactly 9,192,631,770 hertz. In other words, cesium atoms can be made to vibrate in a very steady way, and these vibrations can be readily observed and counted. The second is the time required for 9,192,631,770 of these vibrations to occur.



NIST-F1 Cesium Clock: NIST-F1 is referred to as a fountain clock because it uses a fountain-like movement of atoms to obtain its improved reckoning of time.



Metric System – Time: A brief introduction to the metric system and unit conversions.

Prefixes and Other Systems of Units

SI prefixes precede a basic unit of measure to indicate a multiple or fraction of the unit.

learning objectives

- Apply prefixes to units and distinguish between SI and customary units

Prefixes

A metric prefix, or SI prefix, is a unit prefix that precedes a basic unit of measure to indicate a multiple or fraction of the unit. Each prefix has a unique symbol that is prepended to the unit symbol. The prefix kilo-, for example, may be added to gram to indicate multiplication by one thousand; one kilogram is equal to one thousand grams (1 kg = 1000 g). The prefix centi-, likewise, may be added to meter to indicate division by one hundred; one centimeter is equal to one hundredth of a meter (1 cm = 0.01 m). Prefixes in varying multiples of 10 are a feature of all forms of the metric system, with many dating back to the system's introduction in the

1790s. Today, the prefixes are standardized for use in the International System of Units (SI) by the International Bureau of Weights and Measures.There are twenty prefixes officially specified by SI.

Metric prefixes

Prefix	Symbol	1000^m	10^n	Decimal	Short scale	Long scale
yotta	Y	1000^8	10^{24}	1000000000000000000000000	septillion	quadrillion
zetta	Z	1000^7	10^{21}	1000000000000000000000	sextillion	trilliard
exa	E	1000^6	10^{18}	1000000000000000000	quintillion	trillion
peta	P	1000^5	10^{15}	1000000000000000	quadrillion	billiard
tera	T	1000^4	10^{12}	1000000000000	trillion	billion
giga	G	1000^3	10^9	1000000000	billion	milliard
mega	M	1000^2	10^6	1000000	million	
kilo	k	1000^1	10^3	1000	thousand	
hecto	h	$1000^{2/3}$	10^2	100	hundred	
deca	da	$1000^{1/3}$	10^1	10	ten	
		1000^0	10^0	1	one	
deci	d	$1000^{-1/3}$	10^{-1}	0.1	tenth	
centi	c	$1000^{-2/3}$	10^{-2}	0.01	hundredth	
milli	m	1000^{-1}	10^{-3}	0.001	thousandth	
micro	μ	1000^{-2}	10^{-6}	0.000001	millionth	
nano	n	1000^{-3}	10^{-9}	0.000000001	billionth	milliardth
pico	p	1000^{-4}	10^{-12}	0.000000000001	trillionth	billionth
femto	f	1000^{-5}	10^{-15}	0.000000000000001	quadrillionth	billiardth
atto	a	1000^{-6}	10^{-18}	0.000000000000000001	quintillionth	trillionth
zepto	z	1000^{-7}	10^{-21}	0.000000000000000000001	sextillionth	trilliardth
yocto	y	1000^{-8}	10^{-24}	0.000000000000000000000001	septillionth	quadrillionth

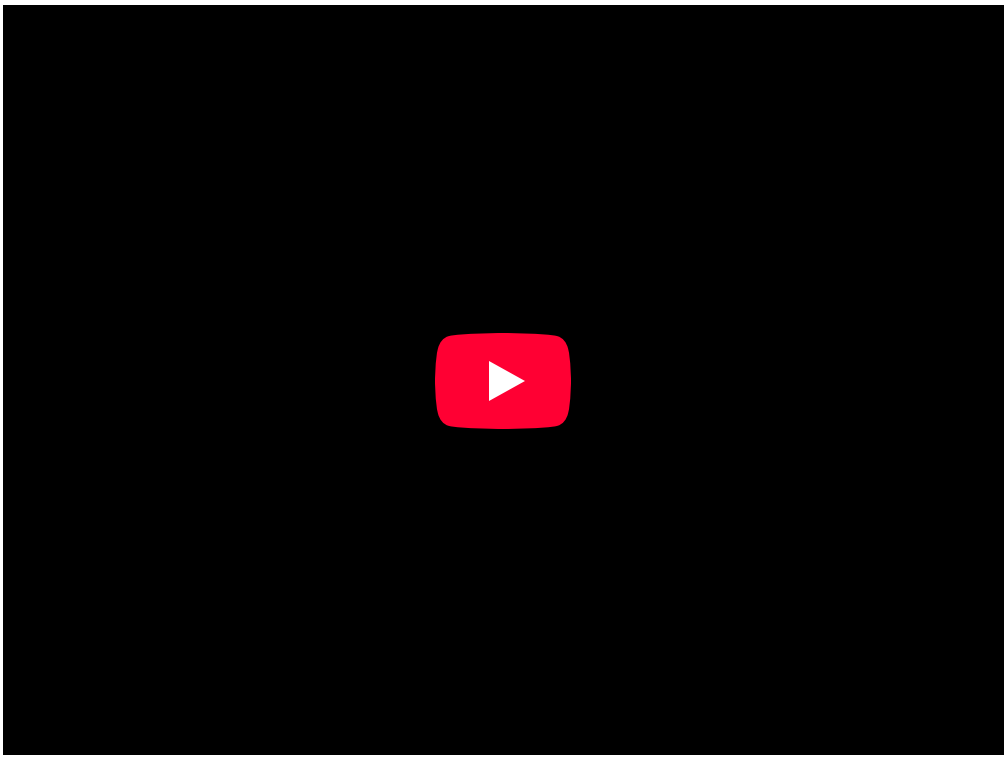
SI Unit Prefixes: The twenty prefixes officially specified by the International System of Units

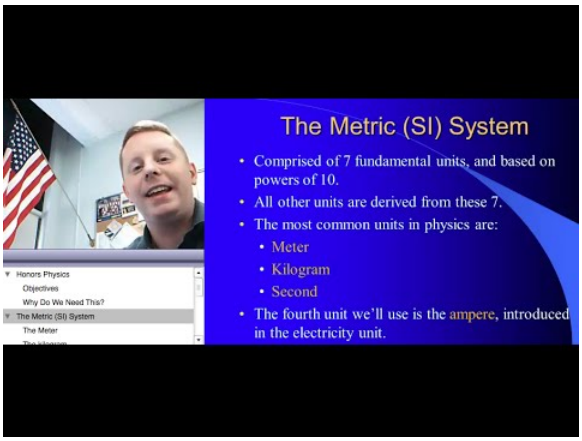
It is important to note that the kilogram is the only SI unit with a prefix as part of its name and symbol. Because multiple prefixes may not be used, in the case of the kilogram the prefix names are used with the unit name “gram” and the prefix symbols are used with the unit symbol “g. ” With this exception, any SI prefix may be used with any SI unit, including the degree Celsius and its symbol °C.

Other Systems of Units

The SI Unit system, or the metric system, is used by the majority of countries in the world, and is the standard system agreed upon by scientists and mathematicians. Colloquially, however, other systems of units are used in many countries. The United States, for example, teaches and uses the *United States customary units*. This system of units was developed from the English, or Imperial, unit standards of the United Kingdom.The United States customary units define measurements using different standards than those used in SI Units. The system for measuring length using the United States customary system is based on the inch, foot, yard, and mile. Likewise, units of area are measured in terms of square feet, and units of capacity and volume are measured in terms of cubic inches, cubic feet, or cubic yards. Units of mass are commonly defined in terms of ounces and pounds, rather than the SI unit of kilograms.Other commonly used units from the United States customary system include the fluid volume units of the teaspoon, tablespoon, fluid ounce, US cup, pint, quart, and gallon, as well as the degrees Fahrenheit used to measure temperature.

Some units that are widely used are not a part of the International System of Units and are considered Non-SI Units. These units, though not officially part of SI Units, are generally accepted for use in conjunction with SI units. These can include the minute, hour, and day used in temporal measurements, the liter for volumetric measurements, and the degree, minute, and second used to measure angles.





Metric System – Prefixes: A brief introduction to the metric system and unit conversions.

Converting Units

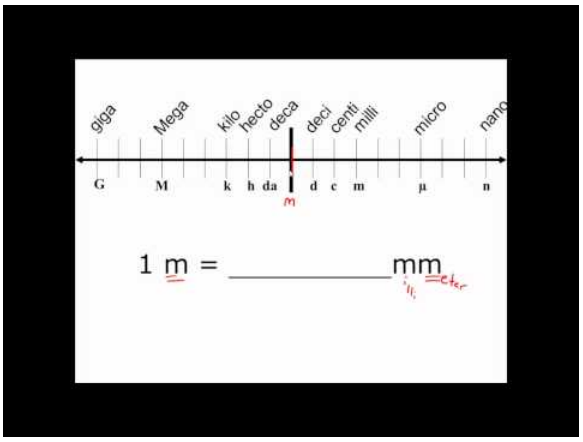
Converting between units can be done through the use of conversion factors or specific conversion formulas.

learning objectives

- Apply factor-label method for converting units

Translating Systems of Measurement

It is often necessary to convert from one type of unit to another. Conversion of units is the conversion of different units of measurement for the same quantity, typically using conversion factors. For example, if you are reading a European cookbook, some quantities may be expressed in units of liters; if you're cooking in the US in a standard kitchen with standard tools, you will need to convert those measurements to cups. Or, perhaps you are reading walking directions from one location to another and you are interested in how many miles you will be walking. In this case, you will need to convert units of feet to miles. This is a bit like translating a substitution code, using a formula that helps you understand what one measure means in terms of another system.



Unit Conversion in the Metric System: EASY Unit Conversion in the Metric System – This simple extra help video tutorial explains the metric system and how to make simple metric conversions.

Conversion Methods

There are several ways to approach doing conversions. One commonly used method is known as the Factor-label method for converting units, or the “railroad method. ”

The factor-label method is the sequential application of conversion factors expressed as fractions and arranged so that any dimensional unit appearing in both the numerator and denominator of any of the fractions can be cancelled out until only the desired set of dimensional units is obtained. For example, 10 miles per hour can be converted to meters per second by using a sequence of conversion factors.

Each conversion factor is equivalent to the value of one. For example, starting with 1 mile = 1609 meters and dividing both sides of the equation by 1 mile yields $\frac{1 \text{ mile}}{1 \text{ mile}} = \frac{1609 \text{ meters}}{1 \text{ mile}}$, which when simplified yields $\mathbf{1 = \frac{1609 \text{ meters}}{1 \text{ mile}}}$. Physically crossing out the units that cancel each other out will also help visualize what’s left over.

$$1 \text{ year} \times \frac{365 \text{ days}}{1 \text{ year}} \times \frac{24 \text{ hours}}{1 \text{ day}} \times \frac{60 \text{ min}}{1 \text{ hour}} \times \frac{60 \text{ s}}{1 \text{ min}} = \\ = 3.15 \times 10^7 \text{ s}$$

Converting 1 year into seconds using the Factor-Label Method: Physically crossing out units that cancel out helps visualize the “leftover” unit(s).

So, when the units mile and hour are cancelled out and the arithmetic is done, 10 miles per hour converts to 4.47 meters per second.

A limitation of the factor-label method is that it can only convert between units that have a constant ratio that can be multiplied, or a multiplication factor. This method cannot be used between units that have a displacement, or difference factor. An example is the conversion between degrees Celsius and kelvins, or between Celsius and Fahrenheit. For these, it is best to use the specific conversion formulas.

For example, if you are planning a trip abroad in Spain and the weather forecast predicts the weather to be mostly cloudy and 16°C, you may want to convert the temperature into °F, a unit that you are more comfortable interpreting. In order to do this, you would need to know the conversion formula from Celsius to Fahrenheit. This formula is: $[°F] = [°C] \times \frac{9}{5} + 32$.

$$[°F] = [°C] \times \frac{9}{5} + 32 \tag{1.2.1}$$
$$[°F] = 28.8 + 32 \tag{1.2.2}$$
$$[°F] = 60.8 + 32 \tag{1.2.3}$$

So you would then know that 16°C is equivalent to 60.8°F and be able to pack the right type of clothing to be comfortable.

Key Points

- The SI unit for length is the meter.
- One meter is defined as the distance that light travels in a vacuum in $\frac{1}{299,792,458}$ of a second.
- Derivatives of measurement units related to the meter are devised around the convenience of the number 10.
- The kilogram is the only SI unit directly defined by the artifact itself.
- Mass is a property that does not depend on gravitational fields, unlike weight.
- One kilogram is defined as the mass of the International Prototype Kilogram (IPK), a platinum-iridium alloy cylinder.
- One kilogram is almost exactly equal to the mass of one liter of water.
- Time is a physical quantity of duration.
- The SI Unit for time is the second.
- The second is operationally defined in terms of radiation emitted by cesium atoms.
- The twenty standardized prefixes for use in the International System of Units are derived from multiples of 10.
- The kilogram is the only SI unit with a prefix as part of its name and symbol; as such, SI unit prefixes are prepended to the unit gram.
- The United States customary units define measurements based on the English, or Imperial, unit standards.
- Conversion of units is the conversion between different units of measurement for the same quantity, typically through multiplicative conversion factors.
- The factor-label method is the sequential application of conversion factors expressed as fractions in which units appearing in both the numerator and denominator can be cancelled out, leaving only the desired set of units.
- For conversions that have a difference factor, specific conversion formulas should be used.

Key Terms

- **Length**: How far apart objects are physically.
- **acceleration**: the rate at which the velocity of a body changes with time
- **inertia**: the tendency of an object to resist any change in its motion
- **Radiation**: the emission of energy as electromagnetic waves or as moving or oscillating subatomic particles.
- **prefix**: That which is prefixed; especially one or more letters or syllables added to the beginning of a word to modify its meaning; as, pre- in prefix, con- in conjure.
- **conversion**: a change between different units of measurement for the same quantity.

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1.3: Significant Figures and Order of Magnitude

Scientific Notation

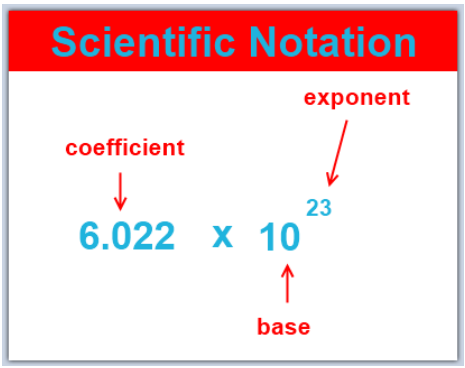
Scientific notation is a way of writing numbers that are too big or too small in a convenient and standard form.

learning objectives

- Convert properly between standard and scientific notation and identify appropriate situations to use it

Scientific Notation: A Matter of Convenience

Scientific notation is a way of writing numbers that are too big or too small in a convenient and standard form. Scientific notation has a number of useful properties and is commonly used in calculators and by scientists, mathematicians and engineers. In scientific notation all numbers are written in the form of $a \cdot 10^b$ (a multiplied by ten raised to the power of b), where the exponent b) is an integer, and the coefficient (a is any real number.



Scientific Notation: There are three parts to writing a number in scientific notation: the coefficient, the base, and the exponent.

Most of the interesting phenomena in our universe are not on the human scale. It would take about 1,000,000,000,000,000,000,000 bacteria to equal the mass of a human body. Thomas Young's discovery that light was a wave preceded the use of scientific notation, and he was obliged to write that the time required for one vibration of the wave was "$\frac{1}{500}$ of a millionth of a millionth of a second"; an inconvenient way of expressing the point. Scientific notation is a less awkward and wordy way to write very large and very small numbers such as these.

A Simple System

Scientific notation means writing a number in terms of a product of something from 1 to 10 and something else that is a power of ten.

For instance, $32 = 3.2 \cdot 10^1$

$320 = 3.2 \cdot 10^2$

$3200 = 3.2 \cdot 10^3$, and so forth…

Each number is ten times bigger than the previous one. Since 10^1 is ten times smaller than 10^2, it makes sense to use the notation 10^0 to stand for one, the number that is in turn ten times smaller than 10^1. Continuing on, we can write 10^{-1} to stand for 0.1, the number ten times smaller than 10^0. Negative exponents are used for small numbers:

$3.2 = 3.2 \cdot 10^0$

$0.32 = 3.2 \cdot 10^{-1}$

$0.032 = 3.2 \cdot 10^{-2}$

Scientific notation displayed calculators can take other shortened forms that mean the same thing. For example, $3.2 \cdot 10^6$(written notation) is the same as $3.2E+6$ (notation on some calculators) and 3.2^6 (notation on some other calculators).

Round-off Error

A round-off error is the difference between the calculated approximation of a number and its exact mathematical value.

learning objectives

- Explain the impact round-off errors may have on calculations, and how to reduce this impact

Round-off Error

A round-off error, also called a rounding error, is the difference between the calculated approximation of a number and its exact mathematical value. Numerical analysis specifically tries to estimate this error when using approximation equations, algorithms, or both, especially when using finitely many digits to represent real numbers. When a sequence of calculations subject to rounding errors is made, errors may accumulate, sometimes dominating the calculation.

Calculations rarely lead to whole numbers. As such, values are expressed in the form of a decimal with infinite digits. The more digits that are used, the more accurate the calculations will be upon completion. Using a slew of digits in multiple calculations, however, is often unfeasible if calculating by hand and can lead to much more human error when keeping track of so many digits. To make calculations much easier, the results are often 'rounded off' to the nearest few decimal places.

For example, the equation for finding the area of a circle is $\mathbf{A = \pi r^2}$. The number π(pi) has infinitely many digits, but can be truncated to a rounded representation of as 3.14159265359. However, for the convenience of performing calculations by hand, this number is typically rounded even further, to the nearest two decimal places, giving just 3.14. Though this technically decreases the accuracy of the calculations, the value derived is typically 'close enough' for most estimation purposes.

However, when doing a series of calculations, numbers are rounded off at each subsequent step. This leads to an accumulation of errors, and if profound enough, can misrepresent calculated values and lead to miscalculations and mistakes.

The following is an example of round-off error:

$$\sqrt{4.58^2 + 3.28^2} = \sqrt{21.0 + 10.8} = 5.64$$

Rounding these numbers off to one decimal place or to the nearest whole number would change the answer to 5.7 and 6, respectively. The more rounding off that is done, the more errors are introduced.

Order of Magnitude Calculations

An order of magnitude is the class of scale of any amount in which each class contains values of a fixed ratio to the class preceding it.

learning objectives

- Choose when it is appropriate to perform an order-of-magnitude calculation

Orders of Magnitude

An order of magnitude is the class of scale of any amount in which each class contains values of a fixed ratio to the class preceding it. In its most common usage, the amount scaled is 10, and the scale is the exponent applied to this amount (therefore, to be an order of magnitude greater is to be 10 times, or 10 to the power of 1, greater). Such differences in order of magnitude can be measured on the logarithmic scale in "decades," or factors of ten. It is common among scientists and technologists to say that a parameter whose value is not accurately known or is known only within a range is "on the order of" some value. The order of magnitude of a physical quantity is its magnitude in powers of ten when the physical quantity is expressed in powers of ten with one digit to the left of the decimal.

Orders of magnitude are generally used to make very approximate comparisons and reflect very large differences. If two numbers differ by one order of magnitude, one is about ten times larger than the other. If they differ by two orders of magnitude, they differ by a factor of about 100. Two numbers of the same order of magnitude have roughly the same scale — the larger value is less than ten times the smaller value.

It is important in the field of science that estimates be at least in the right ballpark. In many situations, it is often sufficient for an estimate to be within an order of magnitude of the value in question. Although making order-of-magnitude estimates seems simple and natural to experienced scientists, it may be completely unfamiliar to the less experienced.

Example 1.3.1:

Some of the mental steps of estimating in orders of magnitude are illustrated in answering the following example question: Roughly what percentage of the price of a tomato comes from the cost of transporting it in a truck?

Guessing the Number of Jelly Beans: Can you guess how many jelly beans are in the jar? If you try to guess directly, you will almost certainly underestimate. The right way to do it is to estimate the linear dimensions and then estimate the volume indirectly.

Incorrect solution: Let's say the trucker needs to make a profit on the trip. Taking into account her benifits, the cost of gas, and maintenance and payments on the truck, let's say the total cost is more like 2000. You might guess about 5000 tomatoes would fit in the back of the truck, so the extra cost per tomato is 40 cents. That means the cost of transporting one tomato is comparable to the cost of the tomato itself.

The problem here is that the human brain is not very good at estimating area or volume — it turns out the estimate of 5000 tomatoes fitting in the truck is way off. (This is why people have a hard time in volume-estimation contests, such as the one shown below.) When estimating area or volume, you are much better off estimating linear dimensions and computing the volume from there.

So, here's a better solution: As before, let's say the cost of the trip is $2000. The dimensions of the bin are probably 4m by 2m by 1m, for a volume of $8\ \mathrm{m}^3$. Since our goal is just an order-of-magnitude estimate, let's round that volume off to the nearest power of ten: $10\ \mathrm{m}^3$. The shape of a tomato doesn't follow linear dimensions, but since this is just an estimate, let's pretend that a tomato is an 0.1m by 0.1m by 0.1m cube, with a volume of $1 \cdot 10^{-3}\ \mathrm{m}^3$. We can find the total number of tomatoes by dividing the volume of the bin by the volume of one tomato: $\frac{10^3\ \mathrm{m}^3}{10^{-3}\ \mathrm{m}^3} = 10^6$ tomatoes. The transportation cost per tomato is $\frac{\$2000}{10^6\ \text{tomatoes}} = \$0.002$ per tomato. That means that transportation really doesn't contribute very much to the cost of a tomato. Approximating the shape of a tomato as a cube is an example of another general strategy for making order-of-magnitude estimates.

Key Points

- Scientific notation means writing a number in terms of a product of something from 1 to 10 and something else that is a power of 10.
- In scientific notation all numbers are written in the form of $\mathrm{a} \cdot 10^{\mathrm{b}}$ (a times ten raised to the power of b).
- Each consecutive exponent number is ten times bigger than the previous one; negative exponents are used for small numbers.
- When a sequence of calculations subject to rounding error is made, these errors can accumulate and lead to the misrepresentation of calculated values.

- Increasing the number of digits allowed in a representation reduces the magnitude of possible round-off errors, but may not always be feasible, especially when doing manual calculations.
- The degree to which numbers are rounded off is relative to the purpose of calculations and the actual value.
- Orders of magnitude are generally used to make very approximate comparisons and reflect very large differences.
- In the field of science, it is often sufficient for an estimate to be within an order of magnitude of the value in question.
- When estimating area or volume, you are much better off estimating linear dimensions and computing volume from those linear dimensions.

Key Terms

- **exponent**: The power to which a number, symbol or expression is to be raised. For example, the 3 in x^3.
- **Scientific notation**: A method of writing, or of displaying real numbers as a decimal number between 1 and 10 followed by an integer power of 10
- **approximation**: An imprecise solution or result that is adequate for a defined purpose.
- **Order of Magnitude**: The class of scale or magnitude of any amount, where each class contains values of a fixed ratio (most often 10) to the class preceding it. For example, something that is 2 orders of magnitude larger is 100 times larger; something that is 3 orders of magnitude larger is 1000 times larger; and something that is 6 orders of magnitude larger is one million times larger, because $10^2 = 100, 10^3 = 1000$, and $10^6 = \text{one million}$

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1.4: Solving Physics Problems

Dimensional Analysis

Any physical quantity can be expressed as a product of a combination of the basic physical dimensions.

learning objectives

- Calculate the conversion from one kind of dimension to another

Dimensions

The dimension of a physical quantity indicates how it relates to one of the seven basic quantities. These fundamental quantities are:

- [M] Mass
- [L] Length
- [T] Time
- [A] Current
- [K] Temperature
- [mol] Amount of a Substance
- [cd] Luminous Intensity

As you can see, the symbol is enclosed in a pair of square brackets. This is often used to represent the dimension of individual basic quantity. An example of the use of basic dimensions is speed, which has a dimension of 1 in length and -1 in time; $\frac{[L]}{[T]} = [LT^{-1}]$. Any physical quantity can be expressed as a product of a combination of the basic physical dimensions.

Dimensional Analysis

Dimensional analysis is the practice of checking relations between physical quantities by identifying their dimensions. The dimension of any physical quantity is the combination of the basic physical dimensions that compose it. Dimensional analysis is based on the fact that physical law must be independent of the units used to measure the physical variables. It can be used to check the plausibility of derived equations, computations and hypotheses.

Derived Dimensions

The dimensions of derived quantities may include few or all dimensions in individual basic quantities. In order to understand the technique to write dimensions of a derived quantity, we consider the case of force. Force is defined as:

$$\mathbf{F} = \mathbf{m} \cdot \mathbf{a} \tag{1.4.1}$$
$$\mathbf{F} = [\mathrm{M}][\mathrm{a}] \tag{1.4.2}$$

The dimension of acceleration, represented as [a], is itself a derived quantity being the ratio of velocity and time. In turn, velocity is also a derived quantity, being ratio of length and time.

$$\mathbf{F} = [\mathrm{M}][\mathrm{a}] = [\mathrm{M}][\mathrm{vT}^{-1}] \tag{1.4.3}$$
$$\mathbf{F} = [\mathrm{M}][\mathrm{LT}^{-1}\mathrm{T}^{-1}] = [\mathrm{MLT}^{-2}] \tag{1.4.4}$$

Dimensional Conversion

In practice, one might need to convert from one kind of dimension to another. For common conversions, you might already know how to convert off the top of your head. But for less common ones, it is helpful to know how to find the conversion factor:

$$\mathbf{Q} = \mathbf{n_1 u_1} = \mathbf{n_2 u_2} \tag{1.4.5}$$

where n represents the amount per u dimensions. You can then use ratios to figure out the conversion:

$$\mathbf{n_2} = \frac{\mathbf{u_2}}{\mathbf{u_1}} \cdot \mathbf{n_1} \tag{1.4.6}$$

Trigonometry

Trigonometry is central to the use of free body diagrams, which help visually represent difficult physics problems.

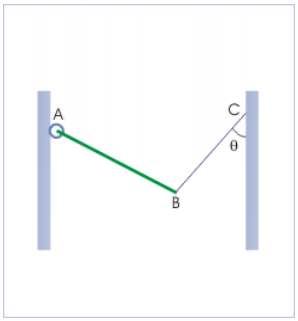
learning objectives

- Explain why trigonometry is useful in determining horizontal and vertical components of forces

Trigonometry and Solving Physics Problems

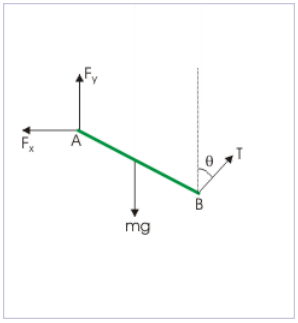
In physics, most problems are solved much more easily when a free body diagram is used. Free body diagrams use geometry and vectors to visually represent the problem. Trigonometry is also used in determining the horizontal and vertical components of forces and objects. Free body diagrams are very helpful in visually identifying which components are unknown and where the moments are applied. They can help analyze a problem, whether it is static or dynamic.

When people draw free body diagrams, often not everything is perfectly parallel and perpendicular. Sometimes people need to analyze the horizontal and vertical components of forces and object orientation. When the force or object is not acting parallel to the *x* or *y* axis, people can employ basic trigonometry to use the simplest components of the action to analyze it. Basically, everything should be considered in terms of *x* and *y*, which sometimes takes some manipulation.



Free Body Diagram: The rod is hinged from a wall and is held with the help of a string.

A rod ‘AB’ is hinged at ‘A’ from a wall and is held still with the help of a string, as shown in. This exercise involves drawing the free body diagram. To make the problem easier, the force *F* will be expressed in terms of its horizontal and vertical components. Removing all other elements from the image helps produce the finished free body diagram.



Free Body Diagram: The free body diagram as a finished product

Given the finished free body diagram, people can use their knowledge of trigonometry and the laws of sine and cosine to mathematically and numerical represent the horizontal and vertical components:

General Problem-Solving Tricks

Free body diagrams use geometry and vectors to visually represent the problem.

learning objectives

- Construct a free-body diagram for a physical scenario

In physics, most problems are solved much more easily when a free body diagram is used. This uses geometry and vectors to visually represent to problem, and trigonometry is also used in determining horizontal and vertical components of forces and objects.

Purpose: Free body diagrams are very helpful in visually identifying which components are unknown, where the moments are applied, and help analyze a problem, whether static or dynamic.

How to Make A Free Body Diagram

To draw a free body diagram, do not worry about drawing it to scale, this will just be what you use to help yourself identify the problems. First you want to model the body, in one of three ways:

- As a particle. This model may be used when any turning effects are zero or have zero interest even though the body itself may be extended. The body may be represented by a small symbolic blob and the diagram reduces to a set of concurrent arrows. A force on a particle is a *bound* vector.
- *rigid extended*. Stresses and strains are of no interest but turning effects are. A force arrow should lie along the line of force, but where along the line is irrelevant. A force on an extended rigid body is a*sliding* vector.
- *non-rigid extended*. The *point of application* of a force becomes crucial and has to be indicated on the diagram. A force on a non-rigid body is a *bound* vector. Some engineers use the tail of the arrow to indicate the point of application. Others use the tip.

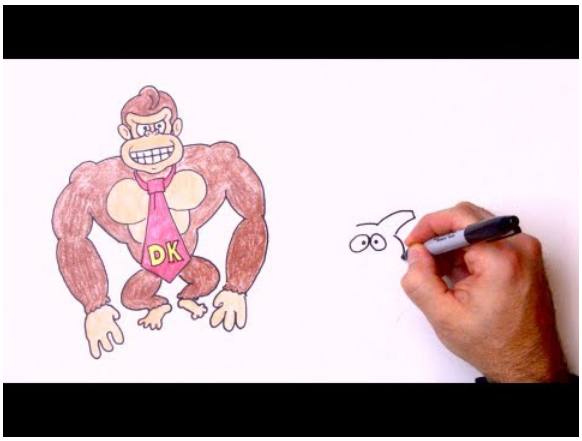
Do's and Don'ts

What to include: Since a free body diagram represents the body itself and the external forces on it. So you will want to include the following things in the diagram:

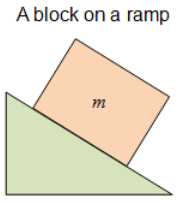
- The body: This is usually sketched in a schematic way depending on the body – particle/extended, rigid/non-rigid – and on what questions are to be answered. Thus if rotation of the body and torque is in consideration, an indication of size and shape of the body is needed.
- The external forces: These are indicated by labelled arrows. In a fully solved problem, a force arrow is capable of indicating the direction, the magnitude the point of application. These forces can be friction, gravity, normal force, drag, tension, etc…

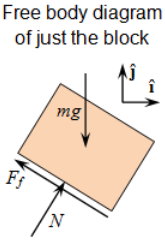
Do not include:

- Do not show bodies other than the body of interest.
- Do not show forces exerted by the body.
- Internal forces acting on various parts of the body by other parts of the body.
- Any velocity or acceleration is left out.



How To Solve Any Physics Problem: Learn five simple steps in five minutes! In this episode we cover the most effective problem-solving method I've encountered and call upon some fuzzy friends to help us remember the steps.





Free Body Diagram: Use this figure to work through the example problem.

Key Points

- Dimensional analysis is the practice of checking relations amount physical quantities by identifying their dimensions.
- It is common to be faced with a problem that uses different dimensions to express the same basic quantity. The following equation can be used to find the conversion factor between the two derived dimensions: $\mathbf{n_2} = \frac{\mathbf{u_2}}{\mathbf{u_1}} \times \mathbf{n_1}$.
- Dimensional analysis can also be used as a simple check to computations, theories and hypotheses.
- It is important to identify the problem and the unknowns and draw them in a free body diagram.
- The laws of cosine and sine can be used to determine the vertical and horizontal components of the different elements of the diagram.
- Free body diagrams use geometry and vectors to visually represent physics problems.
- A free body diagram lets you visually isolate the problem you are trying to solve, and simplify it into simple geometry and trigonometry.
- When drawing these diagrams, it is helpful to only draw the body it self, and the forces acting on it.
- Drawing other objects and internal forces can condense the diagram and cause it to be less helpful.

Key Terms

- **dimension**: A measure of spatial extent in a particular direction, such as height, width or breadth, or depth.
- **trigonometry**: The branch of mathematics that deals with the relationships between the sides and the angles of triangles and the calculations based on them, particularly the trigonometric functions.
- **static**: Fixed in place; having no motion.
- **dynamic**: Changing; active; in motion.

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