3.1.1.4: Energy and Power

Energy is the capacity to do work and it is measured in *joules*; $\mathrm{J=kg\ m^2/s^2}$. Other common units of energy are the Btu (British thermal unit); the calorie ($1\ \mathrm{cal} = 4.18\ \mathrm{J}$); the *food calorie* ($1\ \mathrm{kcal} = 1000\ \mathrm{cal} = 4186.8\ \mathrm{J}$); the kilowatt-hour ($1\ \mathrm{kWh} = 3,600,000\ \mathrm{J}$). Notice that the calories listed for food are actually a thousand scientific calories each.

There are many forms of energy (all measured in joules) and you can convert from one form to another. The capacity of a musical instrument for converting mechanical energy of vibration (a vibrating guitar string for example) into vibrations in the air determines how loud the instrument will sound.

- ***Work*** is one form of energy. Work is defined scientifically as force times the displacement caused by the force; $W = Fd$. We only count the part of the force that acts in the same direction as the displacement; so a force acting perpendicular to a displacement does not do work. Likewise, if something doesn't move, no work is done.
- ***Kinetic energy*** is energy of motion. If we do work on a ball (apply a force over a distance) and then release it the ball will have kinetic energy. Kinetic energy is directly proportional to mass (double the mass of an object at the same speed and you have twice as much energy) and directly proportional to velocity squared (double the speed of an object and you have four times as much kinetic energy); $KE = 1/2mv^2$.
- ***Gravitational potential energy*** is the energy (work) you can get out of an object due to letting it fall. Or if you do work in lifting a mass against the pull of gravity you store up energy that you can get back by letting it fall. Gravitational potential energy is directly proportional to mass and how high it is: $GPE = mgh$, where $g = 0.8\ \mathrm{m/s^2}$ is the acceleration of gravity.
- You can do work on a spring by either stretching it or compressing it a distance x in which case there is stored ***spring potential energy***. The stiffness of a spring is given by a constant, κ, and the energy stored is $SPE = 1/2\kappa x^2$.
- ***Electromagnetic radiation*** is energy carried in the form of electromagnetic waves. Examples of electromagnetic waves are light, radio signals, Wi-Fi signals, blue tooth, cell phone signals, x-rays, gamma rays, microwaves, infrared, ultraviolet, etc. The difference between each kind of electromagnetic wave is the size of the wavelength and the energy it carries. Except for visible light, we cannot detect electromagnetic waves. In general we need some electronic device to detect electromagnetic signals. For example a car radio turns electromagnetic waves from the radio station into audible sound waves.
- A ***chemical reaction*** occurs when two or more atoms interact by re-arranging where their electrons are located (they may share electrons, donate or borrow electrons, or have other complicated interactions). When this happens energy may be emitted or absorbed in the form of heat and/or electromagnetic waves. A burning candle is an example; the molecules making up the candle are interacting with oxygen and giving off heat (increased random molecular energy) and light (electromagnetic energy). The chemical energy stored in a battery is another example; molecules in the battery can combine in a way to give energy to a flow of electrons in a wire.
- As Einstein famously showed, there are certain types of changes in the nucleus of some atoms that give off heat. This ***nuclear energy*** comes from the atom changing a very small amount of mass directly into energy via $E = mc^2$, where c is the speed of light. In other words, in certain special atoms (called radionuclides) something happens to make the atom either randomly split or give off part of its nucleus. If you could weigh the pieces after the reaction you would find a tiny bit of mass was missing. It is this mass that has been turned into energy via Einstein's famous equation. This is the energy used in nuclear reactors and also the energy source of the sun.

In the above examples there is only one mass or object involved. But we know all matter is made of atoms and chemically bound combination of atoms called molecules that are too small to see, even in a microscope. In a solid these atoms are not stationary but vibrate around an equilibrium position. For liquids and gasses they move relative to each other as you saw in the pressure simulation. In both cases the average kinetic energy is proportional to something we call ***temperature***. Temperature is not a type of energy but is proportional to the internal kinetic energy of the molecules that make up a substance and is measured in fahrenheit, $^\circ\mathrm{F}$, *celsius*, $^\circ\mathrm{C}$, or kelvin, K.

In addition to random kinetic energy molecules can bend, vibrate and rotate in both solids, liquids and gasses. If we place an object that has a high temperature (high internal random motion) in contact with an object that has a low temperature (low random internal motion) energy will flow from the high temperature object to the low temperature object (the molecules of each will bump into each other so they eventually have the same average random energy). When this happens we call the energy that moves from the hot object to the cold object ***heat*** which *is* measured in joules. Notice that heat and temperature are not the same thing. Heat is a flow of energy (measured in Joules) and temperature is a number in celsius that is proportional to the internal kinetic energy of the molecules making up a substance.

There is one other term, related to energy, which is how fast energy is being used or delivered. The rate at which energy is used or work done is called ***power*** and it is measured in *watts*, W, and horsepower ($1 \mathrm{~hp} = 746 \mathrm{~W}$). In the US we use watts for electrical power but hp for mechanical power. It would make more sense to either measure light bulbs in hp or cars in watts so that everything had the same units. Power is directly proportional to the amount of energy delivered and inversely proportional to the time it takes to deliver the energy; $P = W/t$. So accelerating your car up to a certain speed will require the same amount of energy regardless of whether you do it slowly or rapidly. But in order to accelerate faster (reach the same kinetic energy in a shorter time) you need a motor that is more powerful.

Questions on Energy and Power:

Mechanical Energy (work, kinetic, gravitational potential, spring potential, heat)

1. Does a baseball pitcher do any work on a baseball as they throw a ball (before release)?
2. Does a baseball pitcher do any work on a baseball after they release the ball?
3. Suppose you are hired to stand and push on a sheet of plywood to keep it stationary while other workers paint it. Are you doing any work in the physics sense?
4. Does the force of gravity do any work on a ball rolling across the floor? What about a satellite in orbit around the earth?
5. We know that for every force on an object there is an equal force in the opposite direction (Newton’s third law). So if you push a filing cabinet across the floor and there is an equal force pushing back on you, does this mean you do no work on the cabinet? Explain.
6. Bullets leaving a rifle typically are traveling at a much higher velocity (more kinetic energy) than bullets leaving the barrel of a pistol. This has something to do with the length of the barrels. Explain.
7. What is the difference between “conserving energy” (i.e. turning off lights, turning the thermostat down) and conservation of energy (a law of physics)?
8. Suppose a $10 \mathrm{~kg}$ mass is held at a height of one meter so that it has a potential energy of $100 \mathrm{~J}$. Answer the following:
   a. If it is released, how much kinetic energy does it have right before it hits the floor?
   b. How much kinetic energy does it have when it is half way down?
   c. What happens to this energy after the mass comes to rest on the floor?
9. A simple pendulum consists of a mass swinging back and forth at the end of a long string or rope. When is the gravitational potential energy a maximum? When it the kinetic energy a maximum? What is the relationship between the kinetic energy and the gravitational potential energy?
10. Describe the changes in types of energy when you throw a ball up into the air during each of the following steps:
    a. You apply a force over a distance to get the ball started;
    b. You release the ball and it starts upward;
    c. The ball slows at it goes upwards until it reaches its highest point;
    d. The ball turns around and begins increasing speed on the way down;
    e. Just before the ball reaches the ground it has its maximum speed;
    f. The ball hits the ground and comes to rest.
11. A kid reaches the bottom of a slide in the playground with $1200 \mathrm{~J}$ of kinetic energy. Based on the height of the slide he had $1400 \mathrm{~J}$ of potential energy at the top. What happened to the missing $200 \mathrm{~J}$?
12. Years ago the Wham-O company sold a “superball” with the claim that it would bounce higher than the height at which it was dropped. Is this possible? Explain.
13. Is it possible to build a rollercoaster that has peaks that are higher than the starting point without using any motors? Explain.
14. A Ping-Pong ball and a golf ball have the same kinetic energy. Which has the higher speed?
15. Helium molecules are lighter than oxygen molecules. In a mixture of these gasses at the same temperature they have the same kinetic energy. Which type of molecule is moving faster?
16. Suppose you do $25 \mathrm{~J}$ of work on a guitar string by stretching the middle it to some maximum position. Then you let it go.

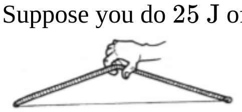

Figure $3.1.1.4.1$

    a. How much kinetic energy does the string have when it passes through its equilibrium (straight) position?

Figure $3.1.1.4.2$

b. How much potential energy does the string have when it reaches the maximum in the other direction?

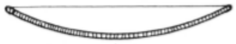

Figure $3.1.1.4.3$

c. What happens to the energy when, after a while, the string comes to rest?

17. Why do the brakes on your car get hot when you stop?
18. Does a car burn more gasoline if the lights are on? What about if the engine is off? Does the gas mileage change in either case? Explain.
19. A gasoline engine only converts about 20% of the energy in the gasoline into useful mechanical energy (making the car go, running the lights, etc.). What happens to the rest of the energy?
20. If a car engine could be 100% efficient (it cannot), would it give off heat? What about sound? What about vibrations?
21. Calories are another unit for energy (a food calorie, like is listed on a soft drink can is actually 1000 calories). We need energy to generate body heat and to move around. What happens over time to someone if input calories (what you eat) is less than the output calories (body heat and movement)? What happens if someone takes in more calories than they burn?
22. Why would you expect the temperature of a jar of water to increase when shaken vigorously?
23. The temperature of the water at the bottom of a waterfall is slightly higher than at the top. Explain why.
24. Suppose there is a sudden loud sound in a closed room. Eventually the sound dies away. What happened to the energy in the sound waves that were produced? What can you say about the temperature of the walls of the room after the sound has died away?

Power

1. If the power company can't provide enough electricity fast enough, is this a power crisis or an energy crisis? Explain.
2. When you reach the top of a hill, have you used more power if you go straight up versus if you take a zigzag path (Hint; it takes more time to walk the zigzag path)?
3. Betty and Bob have the same mass and race up the stairs. Betty gets there first. Who does more work? Who uses more power?
4. Use a calculator to find out how many horsepower a 100 Watt light bulb is capable of putting out. ($1\text{ hp} = 746\text{ Watts}$)
5. Use a calculator to find out how many Watts a 250 hp car motor is capable of putting out.

Thermodynamics

1. An inventor claims to have the following new system. An engine runs by burning hydrogen. The engine turns a generator that makes electricity. The electricity runs through water to make hydrogen. The hydrogen is used in the engine. The inventor claims the system produces more energy than it uses. Should you invest in this new system? Why not (name the law which is broken)?
2. An inventor claims to have invented a motor that is 100% efficient. Would you invest in this device? Why not?
3. Why can't a gasoline car engine be 100% efficient?
4. The actual upper limit of efficiency for a gasoline engine is probably something less than 45%. Where does this limit come from?
5. Why do amplifier circuits for electric guitars generate heat?
6. Many instruments (violins and guitars for example) have to be returned after they have been played for a few minutes. This is because they get warmer. One source of the heat that causes them to warm up is heat from the hands of the performer. What other source of heat is involved?