This chapter discusses the physical principles essential for understanding energy flows in residential buildings. Building energy efficiency can't be applied like a recipe or building code because too many variables are involved. Energy specialists need energy principles to understand unusual problems and to cut through the confusion of competing energy-saving claims. Understand the principles underlying comfort, heat flow, and electricity use, and you'll make good decisions about which energy-conserving measures to apply.

Buildings use energy for temperature control, lighting, hot water, appliances, and entertainment. Energy use can be excessive because of heat leakage through building shells, inefficient heating and cooling systems, or lack of awareness of efficient operating principles. Waste can be associated with lights, appliances, and other energy-using household devices because of obsolete design or careless operation.

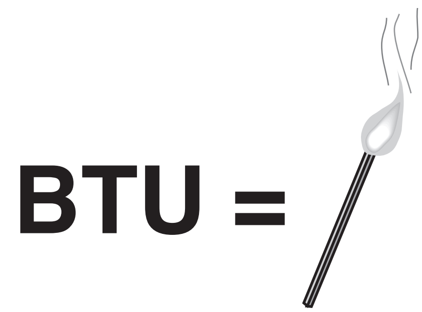
What is Energy?

Energy is a measurable quantity of heat, work, or light. *Potential energy* is stored energy, like a cord of wood. *Kinetic energy* is transitional energy, like a flame.

More than 99% of the energy we use comes from the sun. The only other significant source is nuclear material in the earth. Plants build their tissues with sunlight, and the composition of all fossil fuels is ancient plant and animal tissue. We burn fossil fuels to produce heat and work energy.

We measure energy many ways: therms of natural gas, kilowatt-hours of electricity, barrels of oil, gallons of propane, and pounds of steam are all common measurements of energy. Although energy measurement takes many forms, all types of energy are equivalent.

Measurement of Heat Energy



A kitchen match contains about one BTU of heat energy. One hundred thousand BTUs equals one therm of heat energy.

The energy from last summer's sunshine is chemically locked in the produce we buy at the grocery store. That chemical energy in food is burned in our bodies to provide the kinetic energy and heat required to keep the human machine functioning. Solar energy from the age of the dinosaurs, stored for eons as chemical energy in deposits of coal and oil, provides energy for our modern world.

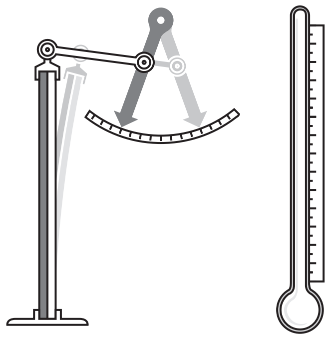
Laws of Thermodynamics

Two laws of the science of thermodynamics govern the behavior of heat in our universe. These laws were first described in the nineteenth century and helped to spawn the industrial revolution. Remember that no device, system, or idea can violate these laws. Attempts have been made but no exceptions have ever been demonstrated.

The first law of thermodynamics says that energy is neither created nor destroyed. Energy merely moves from place to place and changes form. The potential energy of gasoline becomes the automobile's movement, the engine's heat, and tires' friction on the road.

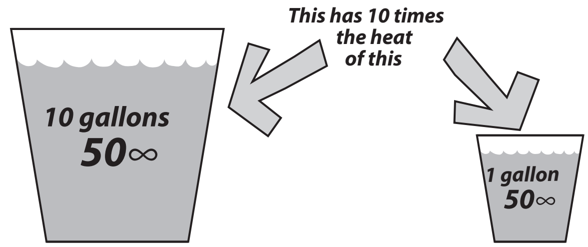
The second law of thermodynamics says that heat moves from high temperature regions to low temperature regions — never the reverse (without additional energy from an external source).

Measuring Temperature



Temperature is measured by the movement of a bimetal element or by the expansion of the liquid metal mercury.

Quantities: Heat and Material



If two different amounts of the same material have the same temperature, the heat content in each is directly related to the mass of the material.

Temperature and Heat

Temperature is a measure of how fast the molecules in a substance are moving or vibrating. Temperature is the average kinetic energy or motion of molecules. Molecules in a solid are stationary, but they vibrate faster and faster as heat is added, raising the temperature.

Heat flows because of a difference in temperature between two places. Heat is measured in *British thermal units (BTU)*, which is the amount of heat required to raise a pound of water's temperature 1°F. A BTU is approximately the amount of heat released by burning one wooden kitchen match. The number of BTUs of heat that a pound of any material absorbs or releases for each degree of temperature change is called its *specific heat*. It is measured in BTUs per pound per degree Fahrenheit (BTU/lb./°F). Water has a specific heat of 1 BTU/lb./°F. It takes only 0.2 BTU to raise a pound of aluminum 1°F, so aluminum has a specific heat of 0.2 BTU/lb./°F. If we add one BTU to a pound of aluminum, it will get 5°F warmer.

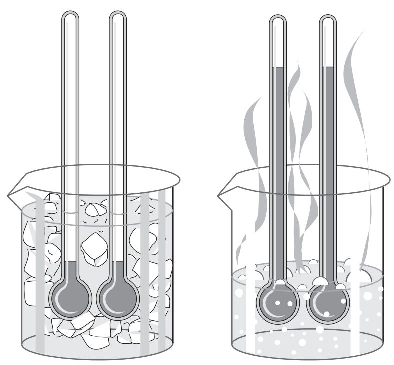
The temperature of a given weight of material tells us how much energy that material contains, which is called *enthalpy*.

Sensible and Latent Heat

The relationship between water's temperature and its heat content is predictable—add a BTU to a pound of water, and by definition, it gets one Fahrenheit degree warmer. Add 150 BTUs to a pound of 50°F water, and its temperature increases 150°F to the temperature of 200°F. This *sensible* relationship ends at 212°F — water's boiling point. With continued heating, the pound of water remains at 212°F, while it absorbs 970 BTUs during its complete evaporation into steam — six times the heat it absorbed going from 50°F to 212°F.

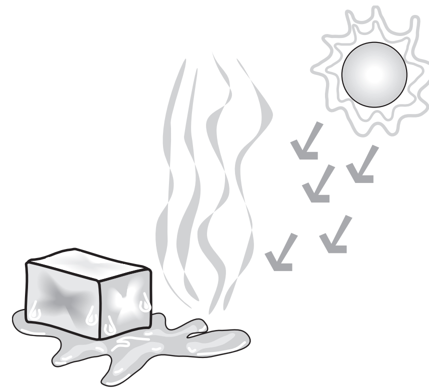
This unexpected or hidden heat, which is released or absorbed as a substance changes form, is called *latent heat*. Our pound of liquid water vaporized when we added 970 BTUs, which is called the *latent heat of evaporation* for water. If we could catch all the steam and recondense it, the 970 BTUs would be released again. This is the principle of steam heating.

Boiling and Freezing Points

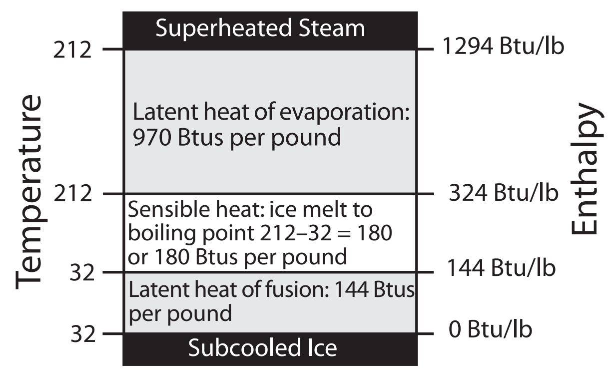


The boiling point and freezing point of water are important to calibrating thermometers because these two states are easy to recognize and duplicate. Freezing point: 32°F or 0°C; boiling point: 212°F or 100°C.

Latent Heat



Latent heat is the heat absorbed or released when a material changes phase between a solid and a liquid or between a liquid and a gas.



At the phase changes, temperature remains constant while enthalpy changes dramatically. Although often considered zero BTUs/lb. enthalpy, ice still has some energy content.

Our pound of water would go through a similar metamorphosis if we were to cool it: the water would lose 1°F for every BTU removed until reaching its freezing point, 32°F. We would then have to remove 144 BTUs — water's *latent heat of fusion* — to turn the pound of water into a block of ice. Conversely, it would take 144 BTUs of heat to melt the pound of ice again.

Steam-heating systems, air conditioners, and refrigerators use latent heat to carry energy from one place to another. In steam heating systems, water is vaporized at a boiler and condensed back to a liquid in radiators. In an air conditioner, a special fluid called a refrigerant vaporizes at the evaporator, absorbing heat from inside the home in the process. The hot gas is then piped outdoors to a condenser, where it *condenses* back to a liquid, releasing its latent heat into the outdoor air.

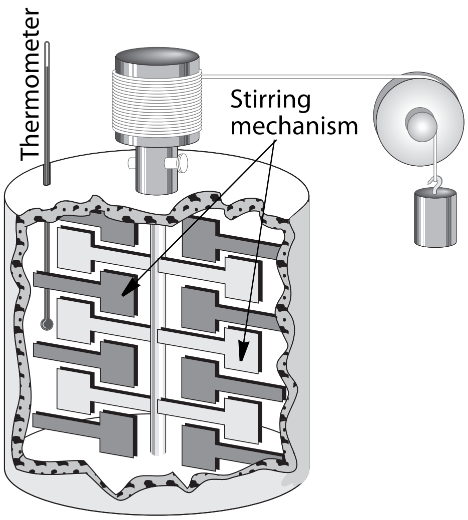
Heat and Work

The American system of measurement has many ways of describing energy — the BTU for heat and the foot-pound for work being two of the most common. If you lift a one-pound weight one foot off the floor, you have done one *foot-pound* of work.

To prove that heat and work are equivalent, a British physicist, James Joule, used mechanical energy (or work) to stir water. He found that for every 778 foot-pounds of work he performed stirring one pound of water, the pound of water absorbed 1 BTU. Joule determined this by measuring temperature change of stirred water in an insulated tank. Now we know that 778 foot-pounds is equivalent to 1 BTU. This was an essential piece of knowledge for the industrial revolution.

The *joule,* an international energy unit, describes both work and heat. A million BTUs (MMBTU) approximately equals a gigajoule (billion joules).

Work Equals Heat



Joule's experiment demonstrated the equivalence of heat and work by stirring water in an insulated tank. For each 778 foot-pounds of work expended to stir the water, he found the water had increased its enthalpy or heat content by 1 BTU.

Energy Versus Power

The differences between energy and power are fundamental, although the two are often confused. At the beginning of this chapter, we defined *energy* as a measurable quantity of heat, work, or light. *Power* is energy divided by time. Power is the rate work is done or heat is released.

Measurements of energy include foot-pounds of work, BTUs of heat, and kilowatt-hours of electricity.

The 100,000-BTUs/hour figure on the nameplate of your furnace is its power rating — its ability to deliver heat to the house when needed. Its power rating is the same in the summer, when it is idle, as in winter, when it's running. The winter operating hours determine how much fuel is converted to heat and how much the occupants pay the utility company.

Power and Energy Units

Power Unit	Energy Unit
BTU/hour (BTUH)	BTU
watt (joule/second)	watt-hour (3600* joules)
kilowatt (1kilojoule/second)	kilowatt-hour (3.6 megajoules)
foot-pound/minute	foot-pounds

* A factor of 3600 is obtained by converting seconds into hours. 60 min. X 60 sec.

One horsepower is 33,000 foot-pounds per minute, and it's a rather antiquated American unit for measuring mechanical power. Electrical power is measured in watts and kilowatts. A watt is actually a joule per second, so, like all power measurements, it is energy divided by time.

To get the quantity of energy produced or consumed, multiply power by the time the energy system is operating. If a 100,000-BTU/hour furnace runs for 10 hours, it converts 1 million BTUs of the fuel's potential energy to heat. If a 1500 watt heater runs for 10 hours, 15,000 watt-hours or 15 kilowatt-hours of electricity is consumed.

If a wood cutter cuts a cord of wood per day (power rating), and works for seven days, then he cuts seven cords of wood (energy). Converting the woodcutter's week of work into BTUs, we would multiply seven cords by 20 million BTUs (the heat content of one cord of hardwood) to get a total of 140 million BTUs of energy collected.

If a wood stove burned a cord in 200 hours of operation, its power would be approximately 100,000 BTUs per hour (20 million BTUs ÷ 200 hours = 100,000 BTUs/hour).

See "Conversion Factors" on page 274.

Pressure Versus Flow

Fluids flow because pressure pushes them along an open path allowing their flow. Both the pressure and a path are necessary for flow. Water, air, heat, and electricity follow similar laws as they flow from place to place — each in a unique way.

Pressure builds because of a difference in some measurable condition between two areas, which are sometimes labeled positive and negative to denote a pressure difference. Heat moves from place to place because of a difference in temperature (°F). Electricity moves because of a difference in electrical energy (volts). The wind blows because of differences in air pressure (pascals, inches of mercury). Water flows downhill because of a difference in altitude (feet). Water vapor flows because of a difference in concentration in water vapor molecules between two areas (pounds of water vapor per pound of dry air).

If a pressure and a path exist, fluids flow from the high-pressure region to the low-pressure region. If the pressure continues, the flow continues. If the pressure equalizes, the flow stops. For example, wind moves air from a high pressure region to a low pressure region, until the pressure difference between the two regions has equalized.

Where there is a pressure difference but no path, there's no flow. A large pressure difference exists between the air inside and outside your car tires, but, hopefully, there is no flow because there are no paths — holes in the tires. If a light switch is turned off, the switch creates a break in the path, interrupting electricity's flow, even though there is voltage — electrical pressure — in the circuit.

The substance connecting two regions may be: a *conductor,* where the medium can flow rapidly; a *resistor*, where the medium flows slowly; or a *barrier*, which stops flow or slows it down to a negligible rate. Glass, for instance, is a heat and light conductor, an electrical resistor, and an air and vapor barrier.

See "Air Pressure and Flow" on page 79 and "Ohm's Law" on page 43 for practical examples.

Energy Transformation and Heat Flow

Energy is neither created nor destroyed. Energy merely flows from place to place and changes form. While it is more accurate to say that energy is transformed or converted to another form, it's more common to say that energy is used or consumed.

Energy Transformation

Potential energy is energy locked in a stable state that can be used for work or heat. Our woodcutter's seven cords of wood remains potential energy until they are burned in a wood stove. Your body converts chemical energy from food to heat and motion. A large snowbank melts to become a million pounds of water flowing through a dam's turbine.

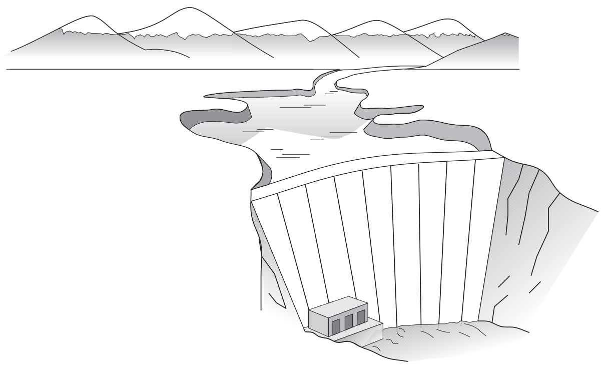
Burning wood or water flowing through the turbine represent kinetic energy. When gasoline explodes in an engine's cylinder, its potential energy becomes the kinetic energy of the rotating crankshaft.

Energy Transport

It is usually more convenient to convert potential energy to kinetic energy at a central location like a power station or boiler room. This confines the heavy machinery, mess, and danger of energy conversion to appropriately designed facilities.

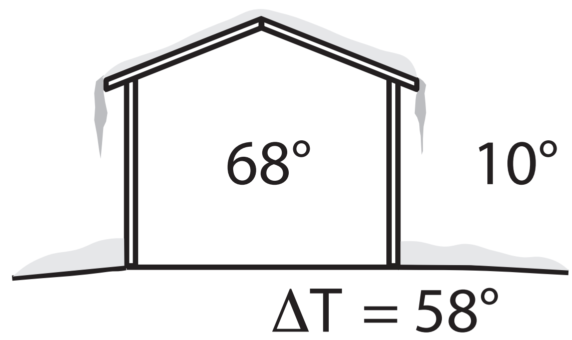
Energy transport is the intentional movement of energy from one place to another. The fuel pump delivers gas to the carburetor, so the engine can burn the fuel. The furnace fan delivers hot air through ducts to the heat registers in the home. Steam pressure moves latent heat from a steam boiler through pipes to radiators. Generators at the power plant push electricity down the wires to your home.

Potential and Kinetic Energy



The dam and snow-capped mountains store water as potential energy. As the water moves through the dam, its potential energy is converted to kinetic energy in rotating electrical generators.

Temperature Difference



The difference in temperature between indoors and outdoors (represented by ΔT) is the driving force for heat flow and presents the need for a heating device to replace the lost energy.

Electricity is the easiest form of energy to move. It flows easily through copper or aluminum wires over long distances.

Mechanical energy is the most difficult type of energy to move. Rotating shafts and belts can move the mechanical energy only a short distance, while a significant part of the energy is dissipated through friction.

Some of the heating energy flowing through pipes and ducts is lost by conduction, convection, and radiation from heated pipes and ducts to their surroundings and also by air, steam, or water escaping from their conduits.

See "Forced-Air Systems" on page 161, "Hot-Water and Steam-Heating Systems" on page 165, and "Electric Circuits and Devices" on page 43.

Types of Heat Flow

Heat travels from areas of high temperature to areas of lower temperature in three ways: *conduction, convection,* and *radiation*.

Conduction is the way heat flows in solids. Heat flows through a solid by the vibrations of its stationary molecules spreading through the material.

Convection is the way heat flows in fluids where the molecules can move around, as in water and air. Winds and ocean currents transmit heat from warm areas to cooler areas around the globe by convection.

Radiation is the way heat flows in a line of sight between bodies of different temperatures. Heat radiation occurs between all objects that can "see" each other through space or through a gas, like air.

***Conduction* —** Conduction is the most familiar and predictable type of heat flow. Heat conducts through solid objects and between objects touching one another. When you grab a hot frying pan, you get burned because the pan's heat conducts into your hand. As an object becomes warmer, the molecules vibrate, bump, and rub against each other more vigorously, passing heat through the material. This flow of heat is always from higher temperature to lower temperature.

The *K-value* or conductance measures the rate of heat conduction through a one-square-foot slab of any material one-inch thick. Metals like aluminum have high K-values, while K-values for insulators like plastic foam are low. The *R-value* is just a measured K-value of a specific product or material.

See "Heat Transmission" on page 59, "Calculating Building Heat Loads" on page 68, "Thermal Transmittance (U-factor)" on page 126 and "Materials/ Building Assembly R-Values" on page 278.

Convection — Convection is heat transferred by a moving fluid like air or water. Convection happens when a part of the fluid moves because of temperature and density differences in the fluid. *Density* measures how many pounds a cubic foot of fluid weighs. Warmer fluid segments with lower density tend to rise, while denser, cooler fluid segments fall.

As heat is added to one part of a fluid, the molecules there race around faster, colliding more often and driving each other further apart. The greater spacing caused by the collisions reduces the density of the heated mass of fluid. The hotter fluid rises, and the cooler, denser fluid descends. The old cliche, "heat rises," is actually incorrect because heat moves in all directions. The truth is, a fluid's hottest molecules rise to the top.

Most convection, which is relevant to residential energy, occurs between a surface and a fluid — between your skin and a cool night breeze, for instance. Hot combustion gases convect against the metal surfaces of a furnace, transferring heat to the metal. Blow on your coffee to cool it, and you are using forced convection.

See "Air Movement" on page 210 for information about convective cooling.

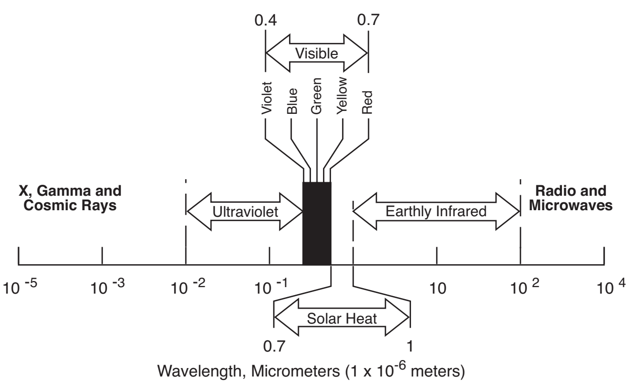
Convection of Fluids

The fluid at the bottom of the kettle is heated by the hot surface of the metal. Warmer fluid is lighter than cooler fluid. The cooler fluid falls and the warmer fluid rises. This is what people mean when they say, "Heat rises." The current caused by this movement is called natural convection.

Radiation — Radiant heat flies through space from one object to another. The sun's radiant heat on your face or a cold window pane sucking radiant heat from the back of your neck are two examples of how you feel radiant heat. Objects, within a line of sight of one another, exchange heat radiation continuously. In this exchange, there is a net heat flow from the high-temperature object to the low-temperature object as dictated by the second law of thermodynamics. The high temperature object gets cooler and the low-temperature object gets warmer as a result of the radiant-heat exchange.

There are two types of thermal radiation important to the study of residential energy efficiency. The first is *solar energy*. The second is *infrared radiation* from objects on earth, emitted as different wavelengths depending on the emitter's temperature. Radiation is actually a continuous spectrum, but we divide types of radiation into solar and infrared to simplify our discussions of these two radiation types because they are important and different from one another.

Electromagnetic Spectrum

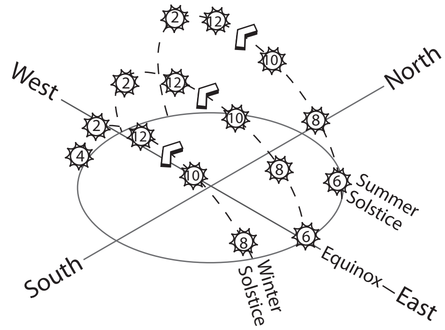


Although the sun emits a wide spectrum of radiation, most of its energy comes as visible light and solar heat — two narrow bands. Earthly infrared radiation is a wider band of wavelength representing a wider variety of temperatures.

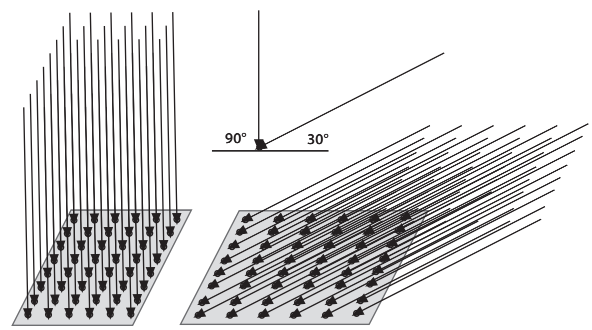
The *electromagnetic spectrum* is a graphic way of describing the types of waves that radiate through our universe. The electromagnetic spectrum runs from short-wavelength x-rays, gamma rays, and cosmic rays, to long-wavelength radio waves and microwaves. Solar energy is a narrow band of this spectrum because of the sun's specific temperature — around 10,000°F. The earth's infrared radiation occupies a wider band on the radiation spectrum relating to the wide temperature variation of the objects in our environment — commonly 0°F to 2000°F.

About 49% of the sun's energy comes to earth as solar heat, 46% comes as visible light, and the remaining 5% is ultraviolet radiation. The earth's ozone layer filters most of the ultraviolet (UV) radiation, which is fortunate, since life on earth wouldn't survive constant bombardment by unfiltered UV rays. The atmosphere absorbs 10% to 20% of incoming solar radiation. Approximately 35% to 40% of the solar radiation is reflected by the earth. The remaining 40% to 55% is absorbed by the earth.

The Sun's Changing Path Across the Sky



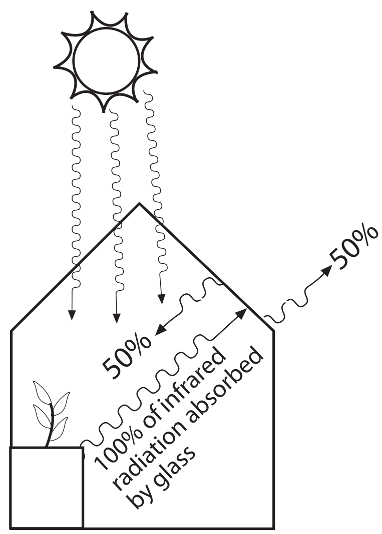
For the Northern hemisphere, the sun is always in the southern sky at noon. In winter, the sun is low, and its rays strike the earth at an indirect angle. In summer, the sun rises higher, its rays strike the earth at a more direct angle, and it stays in the sky longer each day, which accounts for summer's warm weather.



Summer solar radiation strikes the earth at nearly a 90° angle. Winter solar radiation comes from a lower angle; the same solar rays are spread across more surface area, and they travel a greater distance through the atmosphere.

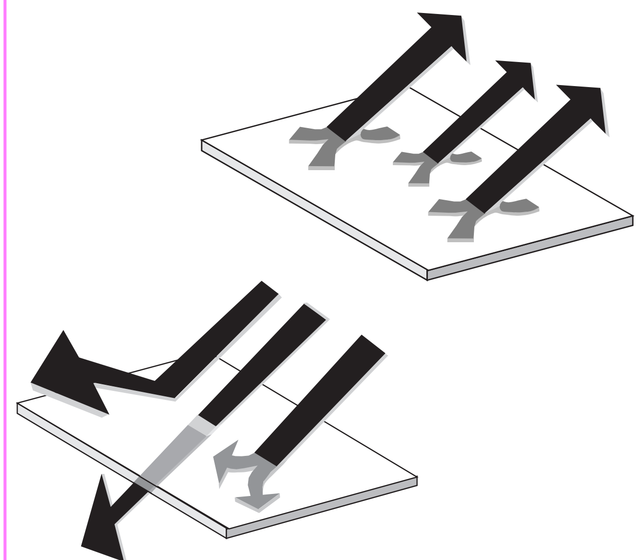
The sun's rays are at their maximum density on a surface at a 90° angle (also called right angle or normal). As the incidence angle varies from normal, solar radiation density decreases. When the sun is directly overhead, its rays are more intense because they travel through less of the earth's heat-absorbing atmosphere. When the sun is lower in the sky, the rays are less intense because they travel farther through the earth's atmosphere.

Greenhouse Effect



Around 87% of solar heat is transmitted by the glass in this greenhouse. The heat is absorbed by objects inside the greenhouse. The objects re-radiate the heat as infrared radiation, which is nearly 100% absorbed by the glass. 50% of that absorbed heat is re-radiated outdoors and 50% is re-radiated indoors. Heat is therefore concentrated in the greenhouse, and its temperature rises as a result of the solar transmission.

Behavior of Radiant Energy



All surfaces emit radiant energy–the amount depends on the temperature and emittance of the surface. Incoming radiation is either absorbed, reflected, or transmitted, depending on the nature of the receiving surface and the angle of the incoming radiation.

The amount of infrared radiation emitted by an object depends on its temperature and its surface characteristics. Warmer objects emit radiant heat more rapidly than cooler ones. Most common objects emit infrared radiation readily. The exceptions are objects with metallized surfaces. The numerical rating of *emittance* is based on a theoretically perfect emitter having an emittance of 1, or 100%. Most common objects have emittances of 85% to 95%. Metallized surfaces like aluminum foil and galvanized steel have emittances of 5% to 20%.

When solar or infrared heat rays strikes an object, the rays are absorbed, reflected, and transmitted, depending on specific properties of that object. These properties are called *absorbance*, *reflectance*, and *transmittance*. Since all radiant heat striking an object is either absorbed, reflected, or transmitted, the values for these properties added together equal 1 or 100%.

Bright white and polished metal objects reflect 80% to 98% of incoming solar energy. Other objects absorb 40% to 95% of incoming solar radiation depending on their color — darker colors absorbing a greater percentage than lighter colors. Glass has special qualities, absorbing or reflecting only 10% to 20% of incident solar radiation and transmitting around 80% to 90% of incident solar radiation.

Most common materials — even glass — absorb almost all incoming infrared heat from earthly objects. The exceptions are polished metal surfaces that reflect most infrared radiation. Polished aluminum, steel, and certain metal alloys of tin, silver, and nickel are the only common substances that reflect both solar and infrared radiation.

See "Conservation Measures for Roofs" on page 207 for information on practical applications.

Glass' solar transmittance and infrared absorptance explain how glass traps heat inside a greenhouse, causing the *greenhouse effect*. Solar heat passes through a greenhouse window and strikes objects inside, warming them. The warm objects in the greenhouse emit infrared heat, which the glass absorbs. Part of that absorbed heat escapes outside, and part radiates and convects back inside, reheating the greenhouse.

Metallized glass coatings called low-e (low emissivity) decrease the glass' emittance. Low-e glass has a greater thermal resistance than un-coated glass because of this low emittance. Metallized coatings also reduce the glass' solar transmittance by reflecting some solar radiation.

See "Solar and Optical Characteristics" on page 127 for more information on glass coatings, and "Heat Gain" on page 203.

Energy, Comfort, Climate

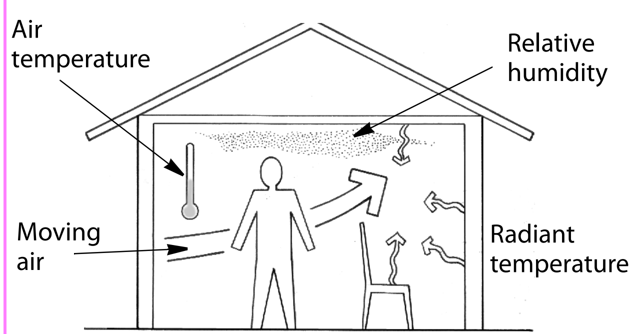
The outdoor climate has the most influence on human comfort of any common factor. The temperature, relative humidity, solar radiation, precipitation, and wind affect the immediate comfort of people outside. The conditions outdoors determine what *space-conditioning* needs to be done to maintain indoor comfort.

We expect more thermal comfort in our homes and offices today than in the past. Individual preferences vary widely, but most people prefer an indoor air temperature of between 65°F and 85°F year-round. The heating and cooling necessary to maintain these temperatures requires between 30% and 70% of an average home's annual energy consumption.

We feel comfortable when we are in a state of thermal equilibrium with our environment without having to sweat or shiver. In thermal equilibrium, the human body is losing as much heat to its surroundings as it is gaining from metabolism.

Air temperature is usually the primary factor determining comfort, while the temperature of walls, ceilings, floors, and furnishings, called *radiant temperature,* is also very important. Together these two temperatures create a composite effect that determines comfort in both summer and winter. A high winter radiant temperature can counteract the comfort effects of low air temperature and vice versa.

Factors Determining Comfort



Comfort in both winter and summer is related to four factors: air temperature, relative humidity, radiant temperature, and air movement.

Temperature

Air temperature is the most noticeable characteristic of climate and the most important factor in determining heating energy use. Outdoor temperature is always changing according to the season, the weather, and the time of day. Heating engineers use a unit of measurement called a *heating degree-day (HDD)* to describe how long the temperature is below 65°F during each day, month, or year. *Cooling degree-days* measure the air temperature differences between the outdoors and 78°F over the hot summer season. The temperatures, from which the degree-day difference is measured, are called the *balance points.*

The *heating balance point* is the outdoor temperature where no indoor heating is needed — usually assumed to be 65°F when the assumed thermostat setting is 70°F. A very well-insulated home may need no heat until the outdoor temperature reaches 50°F, so we'd say that its balance point is 50°F.

The local weather bureau computes the number of heating degree-days daily by figuring how long the average outdoor temperature was below 65°F. If the high was 30°F and the low was 0°F, then the average temperature for that day is 15°F. Subtract that 15°F from the 65°F heating balance point, and you get a 50° temperature difference over one day or 50 heating degree-days.

Heating degree-days are directly related to heating costs. It requires roughly twice as much fuel to heat a home in Duluth, Minnesota, with 9724 heating degree days annually compared to an identical home in St. Louis, Missouri, with 4758 annual heating degree-days.

See "Climatic Data for U.S. Cities" on page 282.

Cooling degree-days measure the intensity of the summer climate. To find cooling degree days, calculate how long the average temperature was above the *cooling balance point* of 78°F by totaling up the daily degree-day values. Cooling degree-days are less reliable as a predictor of summer cooling costs than heating degree-days are for winter heating costs, because amount of shade and relative humidity are often more important than the outdoor air temperature in determining comfort.

See "Calculating Building Heat Loads" on page 68.

Humidity and Moving Air

The air temperature and amount of water vapor in the air determine how much heat the air contains. The higher the humidity at a given temperature, the more heat the air holds. *Relative humidity* (rh) measures how saturated the air is with a percentage of water vapor. Completely saturated air has 100% rh.

Relative humidity is a very important summer comfort factor, since it determines how rapidly sweat can evaporate from the skin. Also, humid air contains more heat than drier air, but this fact exercises less influence on comfort than humidity's sweat suppression. Humid air may feel better to your throat and lungs indoors during winter, but there is little or no heating-energy advantage to higher relative humidity because heat flow depends on temperature difference.

Warmer air can hold more moisture than cooler air. For example, if outside air at 91°F and 50% rh cools to 70°F, the relative humidity rises to 100%. This cooled air contains exactly the same amount of water vapor, but at 91°F, the air is only 50% saturated, while at 70°F, it is 100% saturated. Saturated 91°F air (100% rh) holds twice as much water vapor as the 70°F air at saturation.

The outdoor relative humidity depends on rainfall, nearness to bodies of water, cloudiness, windiness, and other environmental factors. Indoor humidity is governed by the temperature and humidity of outdoor air, the amount of moisture generated within the home's shell, and the rate at which fresh air passes through the home.

When humid air moves near a cool object, tiny beads of water called *condensation* begin to form on its surface (or frost on a freezing-cold surface). Such condensation is undesirable because it fosters the growth of microbes and insects.

Moving air is integral for summer comfort; rapidly moving air increases bodily heat losses through convection and sweat evaporation. Air circulation also is important in winter to avoid air stagnation and large room-temperature variations. However, air currents can reduce comfort in winter if not properly managed.

Keeping indoor relative humidity at less than 60% during the summer promotes comfort, and will prevent condensation on cooler surfaces of an air-conditioned home. Indoor humidity should be less than 40% during cold weather to prevent condensation on cold windows and other surfaces.

See "Water Vapor and Humidity" on page 41 for more information.

Moisture Flow

Moisture flow through buildings is essential knowledge for the energy specialist. This section explains the way water and water vapor move through a building and its materials.

To learn about moisture and health, see "Moisture Management" on page 245.

Characteristics of H_2O

A molecule of water contains two relatively small hydrogen atoms and one relatively large oxygen atom composing the compound with the chemical name H_2O. Water is the only common substance that we encounter in all three of the states of matter: solid, liquid, and gas.

Unlike many other substances, the solid state (ice) is less dense than the liquid. Liquid water expands when it freezes. If the liquid freezes while it is in or near a building material, the movement of the expanding ice can damage the building material.

A water molecule is like a magnet because it has two oppositely charged poles. Liquid water molecules clump together with their positive and negative poles facing one another.

Individual water vapor molecules, floating around in the air, are about one-third of the size of the other air molecules: nitrogen and oxygen. A very small water droplet (fog) is about 3500 times the diameter of a water molecule. A material, like Tyvek and Gortex, can block both liquid water and air, while letting water vapor through. These special materials have pores big enough to pass water vapor but small enough to block air molecules and the smallest water droplets. A material, like polyethylene or aluminum foil, that blocks water vapor also blocks air and liquid water because of this size consideration.

Moisture and Materials

We classify materials as either porous or non-porous to water and water vapor. Porous materials include wood products, insulation, and masonry materials. Non-porous materials, which are impervious to moisture, include glass, plastic, steel, and aluminum.

Adsorption is when porous materials attract and store individual water molecules on the surfaces of their pores. The water-vapor molecules cling to walls of the pores. In drier conditions, the pores *desorb* the water vapor, clinging to their surfaces, and the water vapor exits the material. Many materials such as wood or brick expand and contract with the adsorption and desorption of water vapor.

If the porous material continues adsorbing water vapor, the pores eventually run out of surface area to hold the vapor molecules on the surface of the pores. Then the water molecules start to clump into a liquid, filling the pores with liquid water.

Moisture Movement through Buildings

Moisture enters buildings and moves through them as both liquid water and water vapor. This movement happens in four ways.

- *Liquid flow.* Driven by gravity, or pressure differences, water flows into a building's holes and cracks. Roof leaks and plumbing leaks can deposit large amounts of water in a home.
- *Capillary seepage.* Liquid water creates a suction of its own as it moves through tiny spaces within and between building materials. This capillary suction draws water seepage from the ground. Seepage also redistributes water from leaks, spills, and condensation.
- *Air movement.* Air movement carries water vapor into and out of the building and its cavities. Air pressure difference is the driving force for this air movement, and holes in the building shell are the leakage paths. If the air

reaches saturation (also called the dew point), condensation will occur.

- *Vapor diffusion.* Water vapor will move through solid objects depending on their permeance and the vapor pressure.

Water Vapor and Humidity

Water vapor is lighter than air and the water vapor molecule is smaller than air's other molecules — nitrogen and oxygen. Therefore, water vapor can rise faster and squeeze through smaller microscopic spaces than air. When water vapor moves through a solid material, this is called vapor diffusion.

Materials vary in their permeability to water vapor. Porous materials like brick and insulation transmit water vapor relatively rapidly and are said to have a high permeability. Plywood and drywall have a medium permeability. House wrap is a specially designed material that repels water while letting water vapor through because of house wrap's high permeability. Metals and plastic films, often called *vapor barriers*, slow vapor diffusion to a trickle.

A force called vapor pressure drives vapor diffusion. *Vapor pressure* is created by a difference in the amount of water vapor in two bodies of air, which are separated by some barrier, like a wall. The amount of water vapor in the air — called *absolute humidity* or *humidity ratio* — is expressed in pounds of water vapor per pound of dry air. Vapor pressure is the difference in absolute humidity between two air masses. The greater the vapor pressure, the faster water vapor flows through building materials separating the two air masses.

Relative humidity (rh) — the percentage of the maximum moisture that air at a given temperature can hold — is 100% when the air is saturated with moisture. Add more moisture to saturated air, and moisture condenses on cool objects. Relative humidity is 50% when the air at a particular temperature is only half saturated with water vapor. The moisture content of building materials is directly related to the relative humidity of the air surrounding them.

Converting Energy for Home Use

In all homes, energy is converted from one form to another — electricity to light, gas to heated water — within its walls to provide occupants comfort, water heating, refrigeration, lighting, entertainment, and a variety of other services.

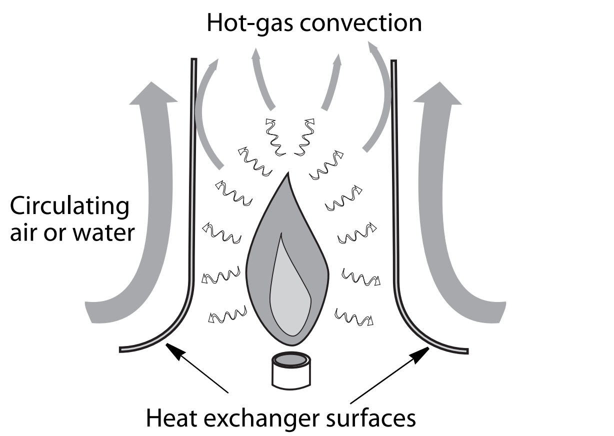
Combustion Heating

Most homes in the United States are heated by combustion heating systems. When the carbon and hydrogen atoms in fuel molecules mix with oxygen and a flame, the chemical chain reaction we call burning begins. Heat is liberated in the chemical process, and we use this heat for space and water heating.

The heat from the flame and hot gases heats a metal structure, called a heat exchanger, which then heats air or water. The flame heats the heat exchanger first and foremost by radiation and also by convection of its combustion gases. Pipes or ducts carry the heated air or water to the building's rooms. The transfer of chemical energy into heat at the flame is usually more than 99% efficient. However the farther the heat travels away from the flame, into the heat exchanger and through the distribution system, the more heat is lost. These progressive heat losses make most central heating systems less than 70% efficient at converting the fuel's chemical energy to useful heat for the home.

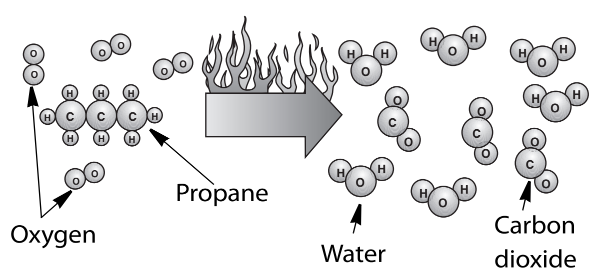
See "Combustion Heating Basics" on page 142.

Heat Transfer from Combustion



The flame heats the surfaces of the heat exchanger by radiation and by convection of the hot combustion gases. Circulating water or air on the heat exchanger's other side conveys the heat to the home.

Combustion of Propane



Propane (C_3H_8) combusts by combining with oxygen (O_2) to form water (H_2O) and carbon dioxide (CO_2).

Electric Resistance Heating

Electric resistance heating changes electricity, usually generated by heat, back into heat. The electric current passes through resistive wires, bars, or plates. Electric heaters are often located in rooms and perform their heating through natural convection and radiation. Electric furnaces blow air through their electric resistance coils. Electric water heaters and heating boilers have their electric resistance bar surrounded by water, so they heat by conduction and convection.

See "Electric Heat" on page 180.

Lighting

Electricity is converted into light in residential buildings in *incandescent* or *fluorescent* lights. In an incandescent light bulb, a tiny metal wire called a filament glows white hot when electric current passes through it. Only 10% of the electricity is converted into light, with the other 90% becoming heat. Fluorescent lamps produce light by passing electric current through a metallic gas. The flow of electricity through the gas excites special chemicals called phosphors, causing them to glow or "fluoresce." The glowing phosphors coat the inside of the fluorescent tube. Fluorescent lamps convert 80% of the electricity they use into light. Using fluorescent lights instead of incandescent lights can reduce the amount of electricity used for lighting by about 75%.

For more information, see Chapter 7 Lighting and Appliances.

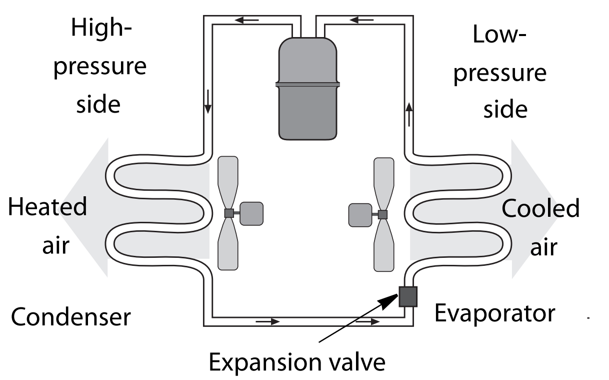
The Refrigeration Cycle

Refrigerators, air conditioners, and heat pumps move heat from one location to another using latent heat. One location is heated and one location is cooled. When liquid *refrigerant* vaporizes in the *evaporator* of an air conditioner, it absorbs heat from the metal in the evaporator coil. The evaporator coil then becomes cold and removes heat from the warm air being blown through the coil. The vaporized refrigerant carries the heat it collected from the indoor air to the *compressor*, where the refrigerant vapor is compressed and sent to the condenser. In the *condenser* the refrigerant condenses back to a liquid, releasing its latent heat of vaporization and heating the condenser coil. The condenser coil has a higher temperature than the air moving through it, so the heat flows from the coil to the air.

The liquid refrigerant collects in the condenser and flows toward the evaporator, pushed by the compressor's pressure. The *expansion device*, which is like a spray nozzle, sprays liquid refrigerant into the evaporator, where it evaporates once again. The evaporating refrigerant removes heat from the evaporator coil, and the cycle repeats.

See "Checking Refrigerant Charge" on page 221 for more detail on the refrigeration cycle.

The Refrigeration Cycle

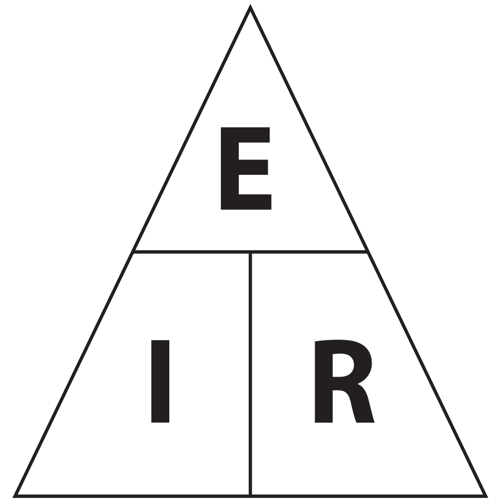


Refrigerant evaporates in the evaporator, absorbing heat from the metal tubes, fins, and passing air. The compressor compresses the refrigerant, preparing it to condense within the condenser. The refrigerant's latent heat is then transferred to the condenser's tubes and fins and then to the passing air.

Electric Circuits and Devices

Electrical principles are presented next because electricity is so important to home energy use. Electricity is the most refined and versatile form of energy. It can be converted into light, heat, or motion. Electricity heats homes, spins motors, lights lamps, cooks, and entertains. Electric circuits providing heat, light, or motion are called *power circuits*. Electricity also regulates most energy-using devices — furnaces, water heaters, and major appliances — using *control circuits*.

Ohm's Law



$$R = E \div I$$
$$I = E \div R$$
$$E = I \times R$$

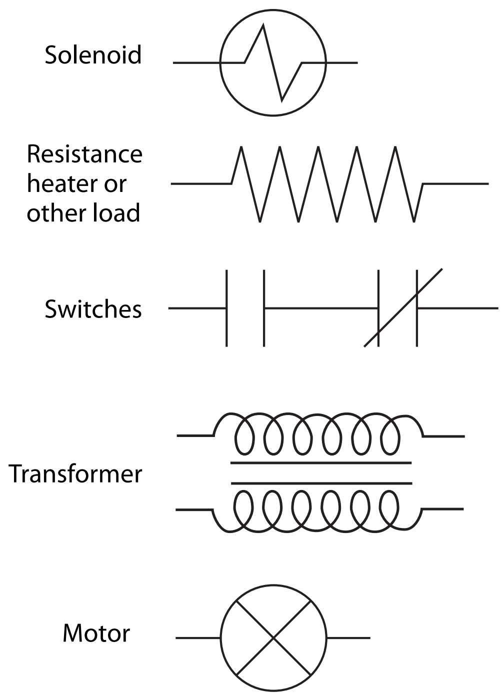
$$P\,(\text{watts}) = E\,(\text{volts}) \times I\,(\text{amps})$$
$$Q\,(\text{energy}) = P\,(\text{watts}) \times t\,(\text{hours})$$

This common representation of Ohm's Law aids in remembering the position of the variables in the formula. E is voltage in volts. I is current in amps. R is resistance in ohms.

An electrical generator pushes electrons through a metal wire, imparting them with electrical energy. Whenever an abundance of electrical energy exists in one area along with a relative lack of electrical energy in another, *voltage* (also called *potential difference*) exists between the two areas. Electricity flows from electrically charged areas to electrically neutral areas. The earth is electrically neutral and is used for the neutral part of circuits.

Most electrical generators are turned by rotating machines called turbines. A turbine is turned by pressurized steam, flowing water, or wind. Heat for the steam turbine comes from the combustion of oil, gas, coal, or thermonuclear reaction.

Electrical Symbols



These are common symbols used in electrical circuit diagrams.

An electric *circuit* consists of three essential parts: a source of electricity; a *path* for the electricity to flow; and a *load*, a device that uses electricity. Most circuits also have a *switch* to start and stop the flow of electricity. The switch creates an air gap in the hot wire of the circuit. We say that a switch is *open* if it is creating an air gap and stopping electricity, and *closed* if it is connecting the circuit.

Electrical Principles

The flow of electricity is described by a well-known formula called Ohm's Law — E (voltage) = I (current) x R (resistance). E stands for *electromotive force*, but is better known as voltage. *Voltage*, expressed in volts, measures the electrical pressure. *Amperes*, or amps, measures current — the flow of electrons. And resistance describes the circuit's opposition to current in units called *ohms.*

Current in amps multiplied by voltage in volts equals the power of the circuit in watts. And watts multiplied by time, in hours, equals watt-hours of energy. This simple relationship between current, voltage, power, and energy is true for electric-resistance devices like heaters and incandescent lights. However, actual energy consumption for motors, transformers, and other devices with coils is less than amperage times voltage because of an effect known as reactance, which is beyond the scope of this discussion.

Series Versus Parallel Circuits

Series circuits form a single looping path from the source to the load and back to the source. The electrical current is the same in all parts of the circuit. Series circuits control heating systems and simple appliances.

Several switches placed in series allow any of these switches to interrupt electrical current to the load. Therefore, a series control circuit can decide that both safety and necessity are present before connecting the load. Both the safety switch and control switch must be closed for electricity to flow to the load.

Parallel circuits form ladder rungs between the hot and neutral wires. In home wiring, each rung is a light, outlet, or appliance. In parallel circuits, voltage is the same on all rungs.

Several switches placed in parallel circuits allow any of these switches to connect a load. Heating and cooling systems often use parallel switches to start the blower — one switch for heating and one for cooling.

Control Circuits

Control circuits are often low-voltage circuits using transformers to step down the voltage. This lower voltage is safer for remote controls and requires smaller and less expensive switches, wiring, and control components. Newer appliances have electronic controls that use even less power than traditional low-voltage control circuits.

A control circuit employs a *controller*, like a thermostat, with a *sensing device*, like a bimetal spring or thermistor to control electric power to a *final control element*, like a gas valve, oil burner, fan, or pump. Controllers and sensing devices may be the traditional electromechanical or the newer electronic types.

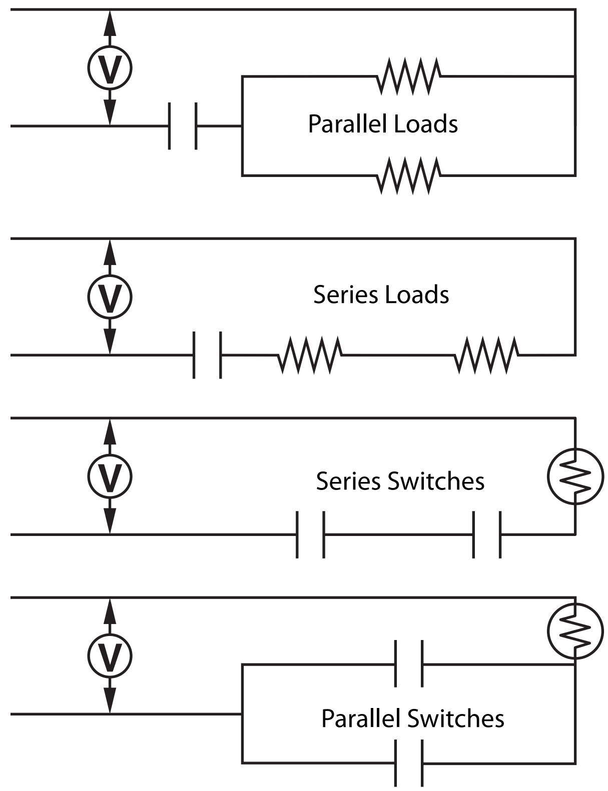
Transformers and Power Supplies

A *transformer* is a device that transforms or changes voltage from one circuit to another. Power companies use high voltage to transport electricity over long distances to reduce line losses, and then step voltage down with transformers to make it safe for local customers.

Step-down transformers within the home reduce voltage from around 115 volts to 24 volts for controlling heating and cooling systems. This lower voltage is safer and more convenient for installing the thermostat without having to run sheathed cable. Dedicated 24-volt controls provide more precise control of energy systems than their 115-volt counterparts.

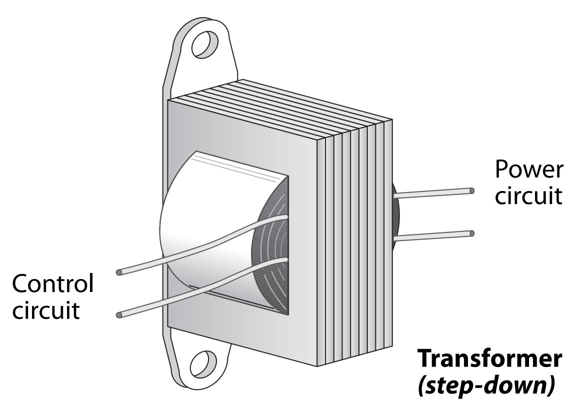
Electronic controls allow even more precise control than low-voltage electromechanical controls. An electronic power supply acts like a transformer to reduce voltages to levels required by the electronic sensing devices and microprocessors. A microprocessor is an electronic brain that can make decisions about control based on a number of inputs.

Types of Electric Circuits



These are the four possibilities for the arrangement of loads and switches in electric circuits.

Transformers

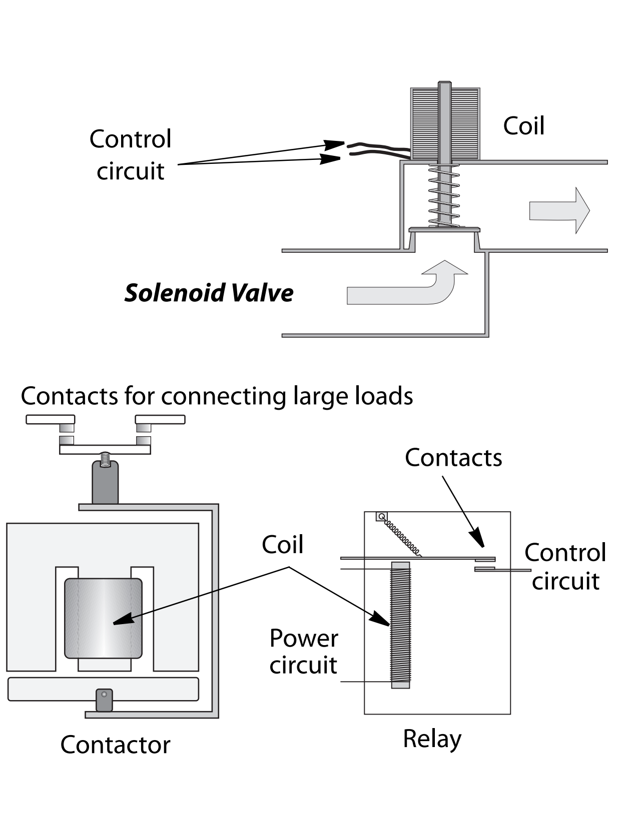


The transformer powers the control circuit to operate a relay for a solenoid valve via a thermostat, aquastat, or limit switch.

Solenoids

A wire coiled around an iron bar will magnetize it, causing it to move when electricity flows through the coil. This principle is called *solenoid action* and is used to open and close solenoid valves and switches called *relays* and *contactors*. An example of a solenoid valve is the automatic gas valve on a gas furnace. Relays are powered by the control circuit. Relays connect and disconnect loads like solenoids and small motors in the power circuit. Larger motors and electric heating elements require sturdier automatic switches called contactors.

Types of Solenoids



Solenoids can operate a switch, like a relay or contactor, or final control element, like a gas valve.

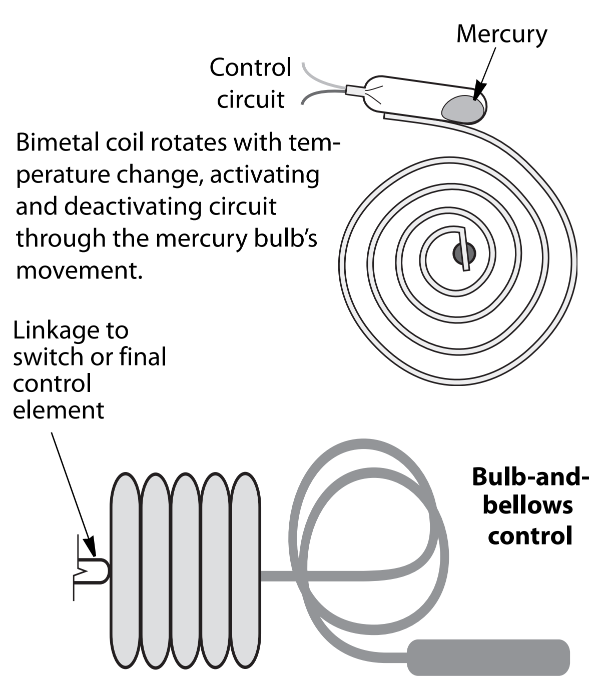
Temperature-sensitive Elements

Bimetal elements or bulb-and-bellows elements move electrical contacts or a valve stem in response to temperature changes. The most common devices using temperature-sensitive elements are thermostats and *limits*. Limits are safety switches that interrupt power if temperatures get too high.

Bimetal elements are temperature-sensitive metal coils and strips. A thermostat uses a bimetal element to turn the heating system on and off. The bimetal element is two thin metal pieces with different rates of expansion bonded together. It bends, rotates, or snaps inside out as the temperature changes. This motion is used to move a switch's contacts or a final control element.

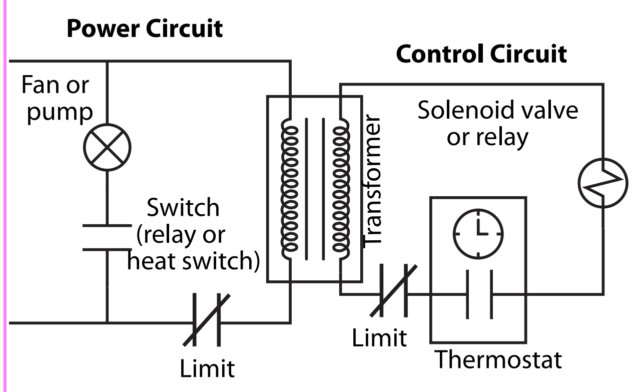
Bulb-and-bellows controls use the variation in volume of a liquid or gas to move electrical contacts or a final control element.

Electromechanical Heat Sensor



A bimetal coil or bulb-and-bellows mechanism can operate an electrical switch or a final control element like a gas valve.

Simple Heating Control Circuit



The transformer is a load in the power circuit and the source of electricity for the control circuit.

Variable Resistors

Variable resistance elements are a part of many electromechanical and electronic control systems. When electricity flows through an electric resistance wire, the electricity is converted to heat. This principle is used by tiny electric resistance heaters that are part of various control devices. Thermostats and electric furnace controls have small resistance heaters combined with their bimetal operators that serve as timers.

Copper wire coiled on a bobbin is also used to sense temperature because the wire's resistance varies significantly with temperature. Variable resistors, called *potentiometers*, are used to tune electronic circuits. Variable electronic resistors are discussed in the next section.

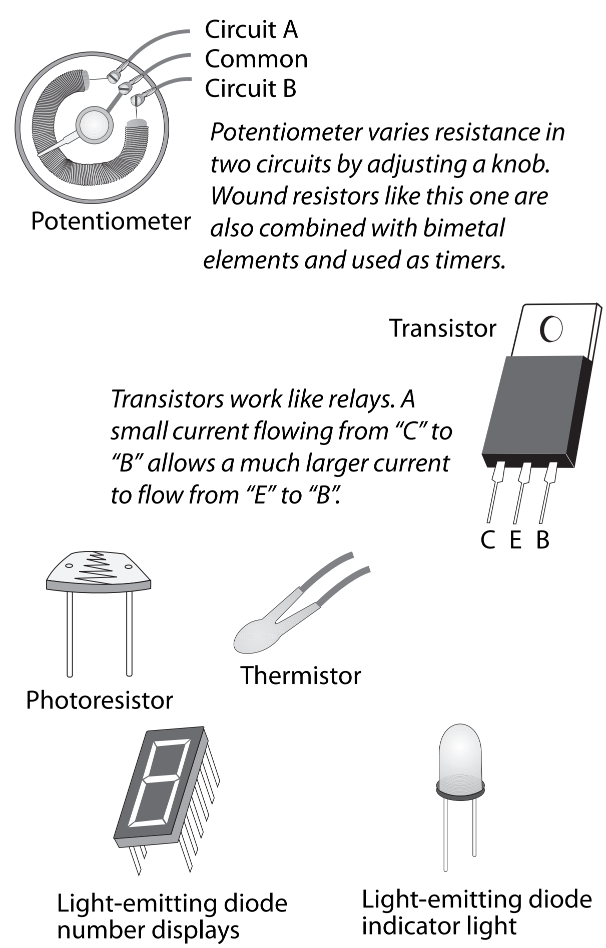
See "Heating Comfort Controls" on page 158 and "Electric Furnaces" on page 180.

Electronic Sensing and Control Devices

Electronic sensors and control devices are part of many sophisticated modern control systems. The most common electronic sensors found in residential control systems are *thermistors* and *photoresistors*. Thermistors sense changes in temperature and photoresistors sense changes in light level. A small sensing current runs from an electronic power supply to a *transistor* through a thermistor, photoresistor, or other electronic sensor, which serves as an automatic switch to activate or deactivate the transistor. The transistor works like a relay to start a burner, compressor, fan, or pump.

A microprocessor can store information entered by the user or collected from sensors for deciding how to operate the system. Electronic control systems are used on many modern heating systems, multifamily lighting and domestic hot water systems, sprinkling systems, and security systems.

Electronic Control Components



It's helpful to understand the functioning of components of electronic control systems.

Home Electrical Wiring

Electrical circuits in homes are mainly power circuits. Power circuits carry 115 volt or 230 volt electricity to an electric device such as a light, fan, pump, or heater. Home power circuits also supply electricity to *duplex receptacles*, which provide power to portable electric devices, such as room heaters and appliances.

Home electrical systems consist of parallel circuits originating in a *main service panel box*. Each of the branch circuits is wired in parallel with the others. The outlets, lights, heaters, and appliances sharing a branch circuit are also in parallel, using the same voltage.

Service Equipment

The 230-volt home electrical system consists of *service wires*; an *electric meter*; *feeder wires*; one or two *main switches*; a *main service panel box* with *circuit breakers* or *fuses*; and the wires, receptacles, and fixtures in the home.

The main service wires come through the ground or overhead from the utility company's transformer. These three wires, two hot wires and a neutral wire, attach to the utility side of the electric meter. Attached to the house side of the electric meter are the feeder wires. The feeder wires are two hot wires (red and black), a neutral wire (white), and an equipment grounding wire (green or bare). The neutral wire and grounding wire are attached together at the meter and attached to a copper grounding rod driven into the earth outside the home. The feeder wires are either part of a cable or are carried in a metal *conduit* (pipe).

The feeder wires run from the meter and main switch into the home's service panel box. The black and red feeder wires are connected to *bus bars,* which hold the breakers or fuses in the panel box. A bus bar is a large electrical terminal where many wires may be connected. The white feeder wire is the neutral and is connected to the neutral bus bar, which is electrically insulated from the panel box. The bare feeder wire is the grounding wire and is connected to the grounding bus bar, where all the ground wires from the branch circuits are also attached.

Branch and Appliance Circuits

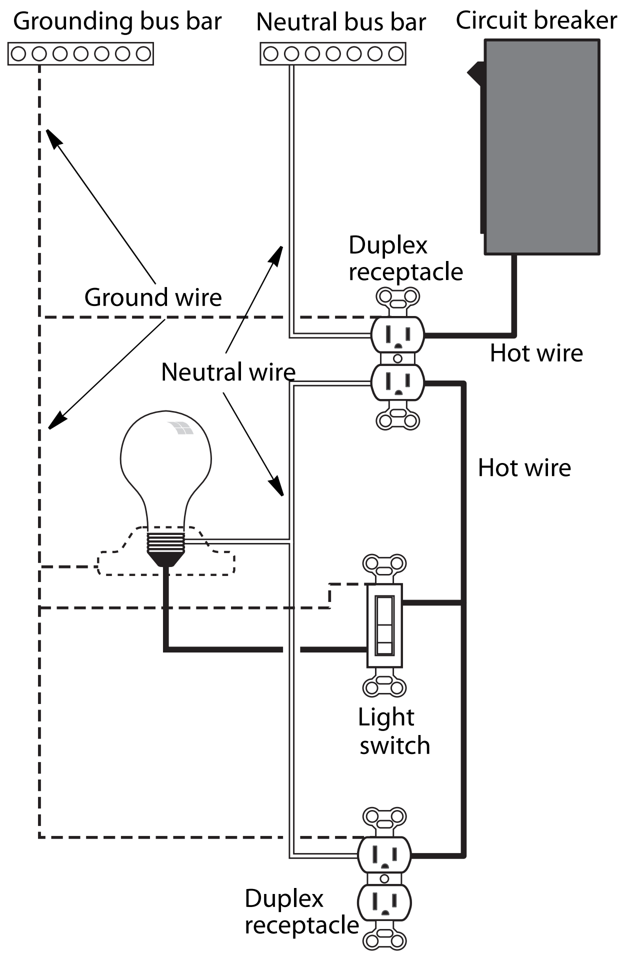
Branch circuits are systems of wire, outlets, and built-in fixtures for lighting, heating, and other purposes. *Appliance circuits* are circuits serving a single appliance like a furnace, air conditioner, electric range, or electric dryer.

The breakers or fuses protect the wire in branch circuits from carrying too much electrical current. When a breaker trips or a fuse blows, the cause of the circuit overload should be found and remedied. If a breaker on a circuit fails, or if the fuse blows, it should be replaced with another having the proper amp rating to match the wire used in the home (15 amps for older home circuits and 20 amps for newer home branch circuits).

Energy auditors should check fuses and breakers before insulating to insure no oversized circuit protectors exist in the panel box. Oversized fuses or breakers will allow excessive amperage to flow, possibly heating the wires. Insulation could make a bad problem worse if the overheated wires are surrounded by the newly installed insulation.

A short circuit is an accidental circuit with no intentional load. Short circuits in appliances are particularly dangerous in the kitchen and bathroom because of the presence of water in those areas. In newer homes, circuits in the kitchen, bathroom, and garage are protected by special breakers known as *ground fault circuit interrupters (GFCI)*. These GFCIs will trip if they detect electricity flowing in the grounding wires. Electricity won't flow in the grounding wires unless there is a short circuit.

Branch Circuit Anatomy



Branch circuits originate at the breaker panel and connect lights and duplex receptacles. This branch circuit powers two duplex receptacles and one light.

It's very important that all hot wires be connected to breakers or fuses, and that neutral wires be connected to the neutral bus bar in the panel box. Sometimes the neutral bus is accidentally connected to a hot wire somewhere in the system. This can happen at an outlet or light, if the hot and neutral wires are reversed. When the wires are reversed at a receptacle, the white wire is connected to the brass-colored terminal and the black wire is connected to the silver-colored terminal of the outlet. This reversal is dangerous, and it can be detected using a *circuit tester*, a plug-in device with lights indicating correct or incorrect wiring.

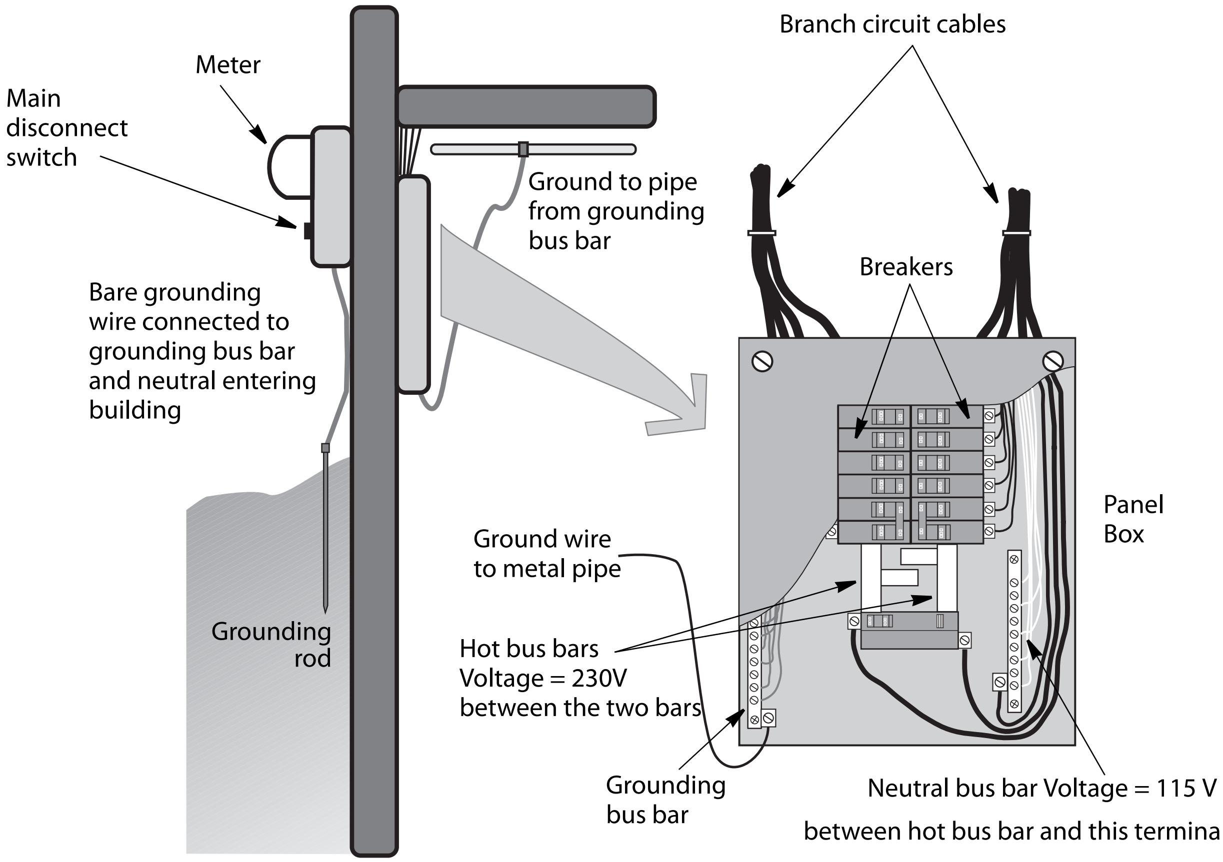
Grounding

Home electrical systems use the earth or the ground in two ways. The first is to ground the neutral feeder wire. The earth is electrically neutral and provides a kind of vacuum that draws electricity from the hot wires toward the earth through the home's electrical devices. The neutral wire is also grounded by the electric utility at the transformer, generator, and other locations in the transmission system.

Equipment used in electrical systems also is grounded. The *equipment grounding* wire is the bare wire connected to: each green grounding terminal of a receptacle; each metal electrical box (including the main panel box); and the metal cabinets of fixtures and appliances. The grounding bus bar in the breaker box is electrically connected to all the branch circuits. This network of equipment grounding connections gives stray electricity an easy and safe path to flow into the ground rather than flowing through some unlucky person in the event of a short circuit.

A bare copper wire also connects the metal piping and sometimes the metal ducts to the grounding bus bar. The home's piping system usually runs into the ground and helps establish a conductive attachment to the ground. However, the main reason for bonding pipes and ducts to a ground is to lead stray current away in the event that a hot wire shorts to a pipe or wire.

Home Electrical System



The major parts of a home electrical system are the service panel and the distribution panel box. The service panel contains the meter and main switch. The distribution panel box contains the breakers or fuses, and the power, neutral, and grounding, bus bars.