

# Heat Transfer: Introduction

As warm-blooded animals, we all care about heat and temperature! Our survival, not to mention comfort, depends on keeping our bodies at a constant temperature, despite huge changes in the environment. The focus here is on buildings, but the same principles apply to our bodies. Every day, we experience conduction (heat transfer through clothes), convection (moving air or water), and radiation (especially sunshine), which are the basic ways that heat is transferred.

In buildings, temperature is a key part of comfort. The more efficiently it can be kept at a comfortable temperature, the better, since a significant part of the nation's energy budget is devoted to the heating and cooling of buildings.

Heat transfer is an important aspect of green building. Heat transfers from warmer to cooler things. This equalizing of temperature occurs in three ways:

*Conduction:* the transfer of heat through a solid material. Heat is transferred directly in and through the substance. Loss of heat through blankets or transfer of heat through the handle of a hot frying pan to your hand are examples of conduction.

*Convection:* the transfer of heat by the movement of fluids such as air or water. Hot air rising up a chimney or hot water circulating in a pot on the stove are examples of convection.

*Radiation:* energy that travels directly through space as electromagnetic waves. It does not require matter for transmission. Most radiation associated with heat is either visible light or infrared radiation, which is not visible. The warmth from a fire is mostly infrared.

In this unit you will explore each means of heat transfer and apply this knowledge to energy efficient house design.

## Before you begin this chapter

Each experiment is simple and quick, but student times for setup and analysis may vary quite a bit. Make a rough schedule for the whole chapter and set clear goals for the students so that the pace doesn't lag. Confirm that the materials are available for each experiment. Some of the experiments involve hot water. An electric kettle is a great source, but very hot tapwater will also do. Warm tapwater will not be hot enough.

## Goals

The purpose of this chapter is to provide students with a basic understanding of the physics of heat transfer in everyday situations. They can then apply this understanding to their engineering challenge in the subsequent chapters.

## Learning goals

Heat is transferred from higher temperature to lower temperature regions until equilibrium is reached.

Students can explain heat capacity and give everyday examples.

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Note: This is one section of the "Science of Heat Transfer" chapter of the Engineering Energy Efficiency Project. See: <http://concord.org/engineering>

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# Heat transfer and thermal equilibrium

Thermal energy is the total kinetic energy of the molecules of a substance. It is the energy needed to raise the temperature of the substance from absolute zero, which is  $-273$  degrees Celsius or  $0$  Kelvin to its actual temperature. It is measured in Joules, kilojoules, or other units of energy.

Heat ( $Q$ ) is the thermal energy that can be transferred between two systems by virtue of a temperature difference. It is much smaller than the total thermal energy because normal temperature differences are small. For example, when a hot drink cools down, it loses thermal energy or heat to the surroundings due to a difference in temperature. When the liquid reaches room temperature it still has lots of thermal energy, but no more heat can be transferred because there is no temperature difference.

Temperature measures the average kinetic energy of the molecules of a substance. Kinetic energy includes all of their motion: vibration, translation, and rotation. Molecules are always moving except at absolute zero, which is defined as the temperature at which all motion stops.

Heat flows from a hotter to a colder body until the two are in equilibrium at the same temperature. The total amount of heat remains the same, unless heat is lost or gained from the system.

This chapter addresses the Massachusetts Engineering / Technology standards which require students be able to 1) differentiate among conduction, convection, and radiation in a thermal system; 2) give examples of how conduction, convection, and radiation are considered in the selection of materials for buildings and in the design of a heating system; 3) explain how environmental conditions such as wind, solar angle, and temperature influence the design of buildings; 4) identify and explain alternatives to nonrenewable energies. The MCAS Physical Science exam always has 13% of its questions on heat.

# Power and energy

Here is a quick review of the difference between energy (how much) and power (how fast).

Take an oil-fired boiler as an example. They are rated by their power output (BTU/hr or energy/time), which can also be expressed as gallons per minute of oil used. How fast the oil is used is a power rating. How many gallons of oil you use is an energy rating.

Here's a very common conversion problem. The energy in a gallon of oil is about 120,000 BTU, and a kWh of energy is about 3400 BTU. If oil is \$3.00/gal and electricity is \$0.15/kWh, which form of energy is more expensive? Show your results.

One gallon of oil is 120,000 Btu \* (1 kWh/3400 Btu) = 35.3 kWh  
At \$3.00/gallon, the cost of oil per kWh is: \$3.00/35.3 kWh = \$0.085/kWh  
Electricity is \$0.15/kWh, so oil is cheaper for the same amount of energy.

Here's another example. A refrigerator uses 600 watts (a unit of power) when it's running. Over the course of a year it runs 10% of the time on average. How many kilowatt hours (a unit of energy) does it use in one year? What does this cost, if electricity is \$0.15/kWh?

The easiest way to do problems like this is to keep canceling units:  
 $600 \text{ W} \times 10/100 \times 24 \text{ hr/day} \times 365 \text{ days/year} \times 1 \text{ kW/W} = 525.6 \text{ kWh/year}$   
 $525.6 \text{ kWh/year} \times \$0.15/\text{kWh} = \text{about } \$80/\text{year}$

# Heat Transfer

## *Thermal energy*

Thermal energy is the total kinetic energy of the molecules of a substance. It is the energy needed to raise the temperature of a substance to its actual temperature from absolute zero, which is -273 degrees Celsius or 0 kelvin. It is measured in joules, kilojoules, or other units of energy.

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# Heat storage

The heat stored in a material, called its heat capacity or thermal mass, is

$$Q = c_p m \Delta T$$

**Q = heat (kJ)**

**$c_p$  = specific heat (kJ/kg K)**

**m = mass (kg)**

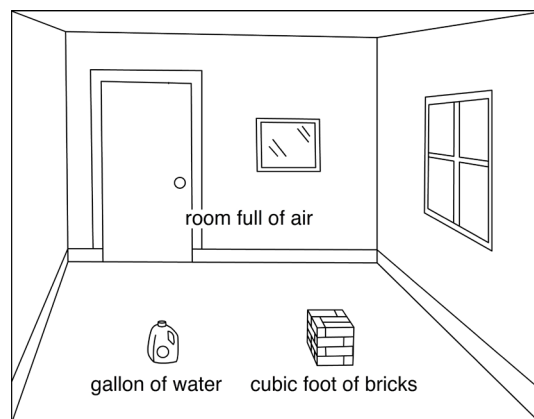
**$\Delta T$  = change in temperature of the material (degrees Kelvin (K), or degrees Celsius ( $^{\circ}\text{C}$ ))**

Expressed in words, this equation says that the heat stored in a material depends on its heat capacity per unit mass (different for different materials), its mass (how much of it there is), and the change in temperature of the object. The symbol ( $\Delta T$ ) means “change in temperature.” It could also be written as ( $T_2 - T_1$ ).

Note the units for  $c_p$  (kJ/kg K). It is the amount of energy that it takes to raise one kilogram of a material one degree Kelvin (which is the same as one degree Celsius).

Note that heat capacity ( $c_p m$ ) is the total heat per degree of temperature change stored in an object. “Heat capacity” is the total heat; “specific heat” is the heat per unit mass. Heat capacity is sometimes called “thermal mass.”

Different materials can store different amounts of heat because they have different specific heats. For example, for a given change in temperature, the same amount of heat is stored in a roomful of air, a cubic foot of bricks, or a gallon of water.



Ask students: What is an example of heat storage? What affects how much can be stored?

Air doesn't hold much heat, and most heat storage in buildings is in the solid materials – plaster walls, concrete floors, etc. Very little of it is in the air, which is quick to heat up, and quick to cool down.

Water has a very high heat capacity, that is, it takes a lot of energy to change the temperature of water a small amount, compared to many other materials. This is very significant in both natural and man-made systems. For example, much more heat is stored in the world's oceans than in its atmosphere, which is important when thinking about climate change. As another example, a much smaller volume of water is needed than air to transport heat from one place to another – say from the furnace to the rooms of a house.

Heat flows from a hotter to a colder body until the two are in thermal equilibrium at the same temperature. The total amount of heat remains the same, unless heat is lost from the system or gained from the outside. This is the principle of Conservation of Energy.

This principle can be used to measure the amount of heat stored in a material. If heat is allowed to flow between two objects at different temperatures, the heat gained by one object (A) is equal to the heat lost by the other one (B).

$$(c_p m \Delta T)_A + (c_p m \Delta T)_B = 0$$
$$(c_p m \Delta T)_A = -(c_p m \Delta T)_B$$

Use this principle to explore the factors that affect heat storage.

Two blocks of aluminum, one at 80° C and the other at 20° C, are placed in contact and surrounded by very good insulation. The warmer block is twice as large as the other. What will be the final temperature of each block? Explain how you figured it out.

The heat lost by one block must equal the heat gained by the other, so the smaller block's temperature must change twice as much as the larger block's temperature. This will be true if the smaller block changes by 40 °C and the larger block changes by 20 °C. The resulting temperature (60 °C) is the weighted average.

# Experiment

## HEAT CAPACITY

### Tools & materials

- Temperature sensor
- Computer
- 200g or greater scale
- Hot tap water
- Cold tap water
- Water at room temperature (left overnight)
- Small paper or thin plastic or Styrofoam sample cups (not glass or ceramic)

One or more of the following test materials:

- Vegetable oil at room temperature
- Detergent to cut the oil
- Small nails at room temperature
- Pebbles at room temperature
- Sand at room temperature

Approximate heat capacities (J/g°C): vegetable oil: 1.7; olive oil 2.0; iron (nails): .45; sand: .84

In this experiment you will compare the specific heat capacity of various materials with a quick and simple test. If two equal masses of water at different temperatures are mixed together, the final temperature of the mixture is halfway between the two starting temperatures. If equal masses of water and some other material are mixed in the same way, the final temperature may not be at the halfway mark. That is the test you will use to compare the heat capacity of other materials to the heat capacity of water.

### Procedure & data collection - Part I

1. Test water against water to practice your technique. Weigh out equal masses of water at different temperatures into two small sample cups. Be sure to tare the scale, that is, subtract the mass of the cup from the measurement. Pick an amount that will fill the mixing cup about three-quarters full when the two are combined.

Note: the greater the difference in temperature of the two samples, the more accurate the result will be.

2. Attach the temperature sensor to the computer.
3. Measure the temperature of each sample.
4. Quickly combine the two samples into a mixing cup, mix them, and measure their resulting temperature. If you are quick about it, the temperature will not drop.
5. Record your results in the table below.

Table 1: Heat capacity

	Water A	Water B	Combination
Mass			
Temperature			
Halfway point $(TempA + TempB) / 2 =$ _____			
Measured combination temperature = _____			
Difference = _____			

## *Analysis*

Since Water A and Water B had the same mass and specific heat capacity, the combination should be at the average temperature of the two. How close were you?

What could account for the difference?



## Procedure & data collection - Part II

1. Test water against oil. Weigh out equal masses of water and oil at different temperatures. Pick the same amount as before.
2. Attach the temperature sensor to the computer.
3. Add a few drops of detergent to the water, so that the oil and water will mix.
4. Measure the temperature of each sample.
5. Quickly combine the two samples, mix them, and measure their resulting temperature.
6. Record your results in the table below.

Table 2: Heat capacity

	Water	Oil	Combination
Mass			
Temperature	$T_w =$	$T_o =$	$T_f =$

## Analysis

Using the equation introduced earlier and doing some algebra (see page 3), the specific heat of oil compared to water is

$$C_{\text{oil}}/C_{\text{water}} = (T_{\text{water}} - T_{\text{final}})/(T_{\text{final}} - T_{\text{oil}})$$

= (change in water temperature) / (change in oil temperature)

Your finding:  $C_{\text{oil}} / C_{\text{water}} =$  \_\_\_\_\_

Is the specific heat capacity of oil greater or less than that of water?

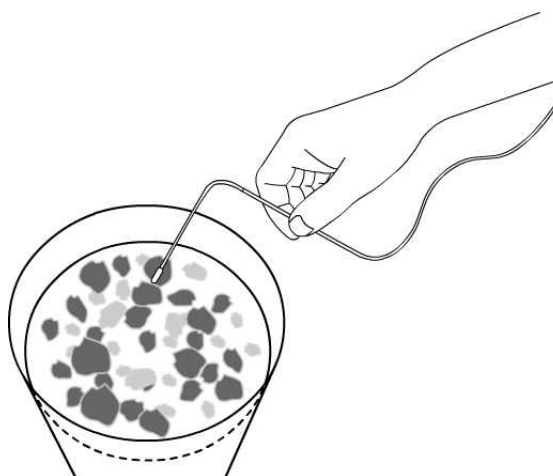
Since  $C_{\text{water}}$  is 4.18 J/g°C, what is  $C_{\text{oil}}$ ? \_\_\_\_\_

### Procedure & data collection - Part III

1. Test water against another material – iron (nails) or rock (pebbles or sand). These have been chosen because they are granular and will quickly reach an equilibrium temperature with water even if they don't mix by dissolving.
2. Attach the temperature sensor to the computer.
3. Make sure the test material has been allowed to come to room temperature by sitting around for an hour or two.
4. Weigh out equal masses of water and test material. Pick the same masses as before.
5. Measure the temperature of each sample. Use room temperature for the test material.
6. Quickly pour the water onto the test material and stir the mixture. Measure their resulting temperature.
7. Record your results in the table below.

Table 3: Heat capacity

	Water	Test material	Combination
Mass			
Temperature	$T_w =$	$T_t =$	$T_f =$



## Analysis

A previously noted,

$$C_{\text{test}}/C_{\text{water}} = (T_{\text{water}} - T_{\text{final}})/(T_{\text{final}} - T_{\text{test}})$$

= (change in water temperature) / (change in test material temperature)

Your finding:  $C_{\text{test}} / C_{\text{water}} =$  \_\_\_\_\_

Is the specific heat capacity of the test material greater or less than that of water?

Since  $C_{\text{water}}$  is 4.18 J/g°C, what is  $C_{\text{test}}$ ? \_\_\_\_\_

Use these as discussion questions. As an extension, present this challenge: "If sunshine is used to heat a house, it is very intense for a few hours and then goes away all night. How does one maintain a constant temperature in the house in that situation, neither too hot during the day or too cold at night?"

Answer: thermal storage capacity will diminish both overheating and cooling off. But it must be thermally connected to the sunlight (light-absorbing surfaces) and the air to be useful.

## Connection to buildings: Heat storage capacity

### Application

How would a building with a high heat capacity (masonry) behave differently from a building with a low heat capacity (wood frame)?

- It would take longer to heat up, if they were both cold to start with.
- The temperature would be steadier.

When and where is it useful to store heat? Think about different contexts, such as houses, food, cooking, or water and give at least three examples.

As a general answer, whenever the heat source is intermittent and a constant temperature is desired.

- In a passive solar house, heat gained during the day should be stored in the walls and floor.
- A crock pot is heavy ceramic, partly to even out the temperature since heat is added in short bursts.
- The ocean stores an enormous amount of heat, which evens out the annual temperature changes in coastal regions.
- A thermos keeps hot drinks hot and cold drinks cold.
- A hot water bottle stores heat in water and releases it slowly to your body.
- A hot water tank typically has enough water for several showers, because the water doesn't heat up again as fast as the shower uses it up.

Rank these materials for their ability to store heat, from most to least: masonry, air, water, wood.

water, masonry, wood, air

# Heat Transfer

## Conduction

### Introduction

Conduction is the transfer of heat through solid materials. Thermal conductivity is the measure of how fast a material conducts heat. The opposite of conductivity is resistivity, or insulating value. Metals, like aluminum or iron, conduct very well, that is, they are good conductors and poor insulators. Materials with air trapped in them, like wool, bedding, or Styrofoam, conduct very slowly; they are good insulators. Most solid materials, like wood, plastic, or stone, are somewhere in between.

### Factors that affect heat conduction

The rate of heat transferred by conduction depends on the conductivity, the thickness, and the area of the material. It is also directly proportional to the temperature difference across the material. Mathematically, it looks like this:

$$\Delta Q/\Delta t = -kA(\Delta T/L)$$

$(\Delta Q/\Delta t)$  = the rate of heat conduction (kJ/s)

$\Delta T$  = temperature difference across the material

$L$  = thickness of the layer (m)

$A$  = area of the material (m<sup>2</sup>)

$k$  = thermal conductivity of the material per unit thickness (kJ/m/s/°C)

The symbol  $\Delta$  (delta) means “change in.” It could also be written as follows:

$$\Delta Q/\Delta t = (Q_2 - Q_1)/(t_2 - t_1)$$

$$\Delta T = (T_2 - T_1)$$

Note that  $\Delta Q/\Delta t$  is the *rate* of heat flow by conduction, that is, how fast it flows through the material. The *amount* of heat flow is  $\Delta Q$ .

Rate of heat flow is in units of power (Joules per second). Amount of heat is in units of energy (Joules). See the end of this activity for a review of the difference between power and energy.

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How does heat flow through solids?

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#### Learning goals

Conduction is the transfer of heat through solids.

Factors that affect rate of heat flow include the conductivity of the material, temperature difference across the material, thickness of the material, and area of the material.

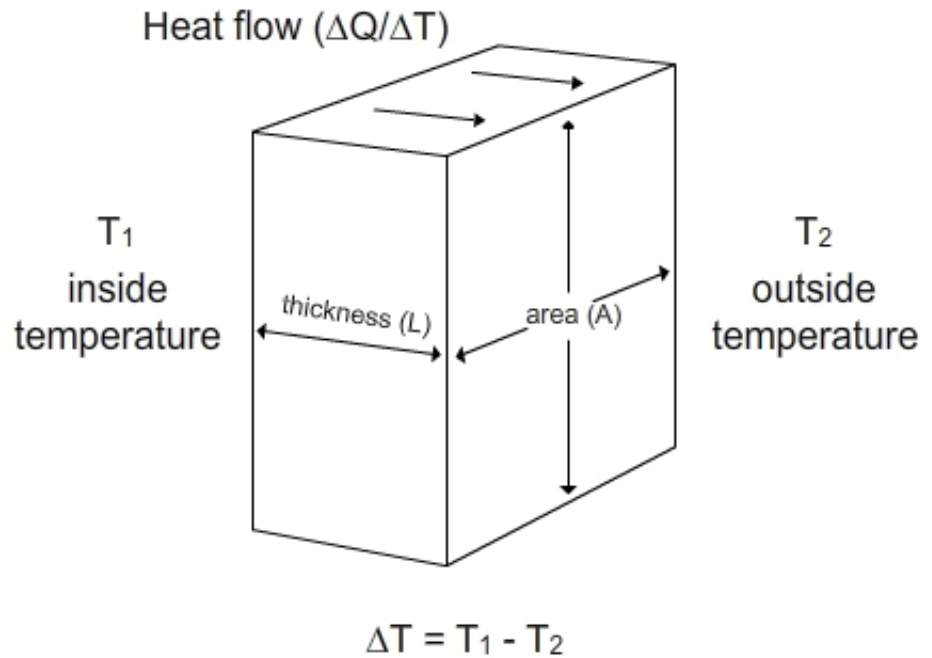
Different materials have greater or lesser resistance to heat transfer, making them better insulators or better conductors.

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Note: This is one section of the “Science of Heat Transfer” chapter of the Engineering Energy Efficiency Project. See: <http://concord.org/engineering>

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Be sure everyone understands the factors in the equation. Have students make up equation-derived sentences, such as "heat flows faster if there is a greater temperature difference, because  $(\Delta Q/\Delta t)$  is proportional to  $\Delta T$ ."



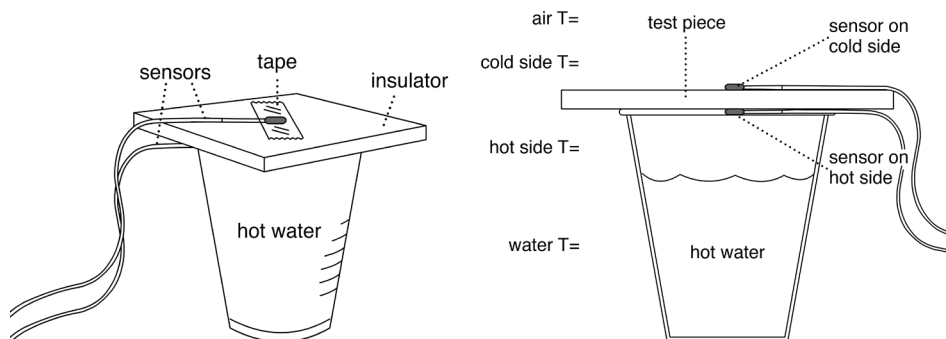
*Factors that affect heat conduction through a solid material.*

# Conductivity of different materials

In this experiment you will measure the relative conductivity of various materials by placing them over a cup of hot water and measuring the temperatures on both sides.

## Procedure & data collection

1. Pick a test material from the available collection of sample squares.
2. Attach the two temperature sensors to the computer.
3. Fill a foam cup with very hot water and bring it to your work station.
4. Measure the room temperature and the hot water temperature by putting one of the sensors first in air and then in the water in the cup. Record them in Table 1 below.
5. Start data collection. Tape a temperature sensor to each side of a piece of material. The tape should cover the sensor and hold it tightly to the surface.



6. Place the material on top of the cup and hold it firmly in place, touching only the edges.
7. Observe the temperature graphs. After they stop changing very quickly (about three minutes), stop data collection and scale the graph.
8. Write down the steady state temperatures in Table 1.

## Tools & materials

- Two fast-response temperature sensors (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensors
- Hot tap water
- Styrofoam cups
- Squares of different rigid materials (aluminum, cardstock, cardboard, foamcore) large enough to cover the cup
- Clear tape

The test piece in this experiment is meant to imitate the wall of a house. The temperature difference across the material is related to its insulating value but is not a strict proportionality.

Be sure that the tape covers each sensor and holds it tightly against the material. Different teams can select different materials or variations (several layers, mixed layers) to test.

Tell students to keep the cup covered all the time to maintain water temperature. Replace with new hot water when the temperature drops.

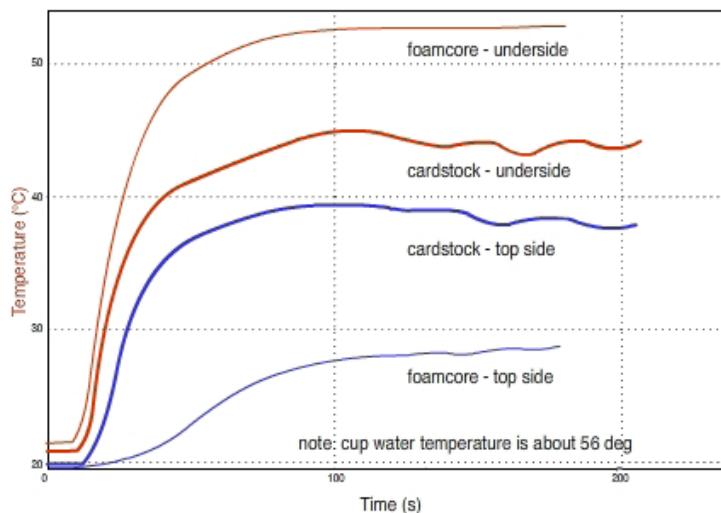


Here are the key observations:

- A greater temperature difference between the surfaces means there was less heat flow, which implies lower conductivity of the material.
- More layers or more thickness reduce heat flow.
- The interior surface temperature of a poorly insulated wall is lower than a well-insulated wall.

If there's time, put up a chart showing results with different materials by different teams.

- Pick another material and repeat steps 5-8. Record all the data as different runs. (To do this in the Vernier software, click on the "store" icon before starting to collect a new dataset.) Here's an example. The thicker lines are the current experiment, and the thinner lines are a previous run.



- Save your data file.

Conductivity of materials					
Material	Water temperature	Air temperature	Inside surface temperature	Outside surface temperature	Difference across material
Initial conditions					
Aluminum					
Cardstock					
Foamcore					

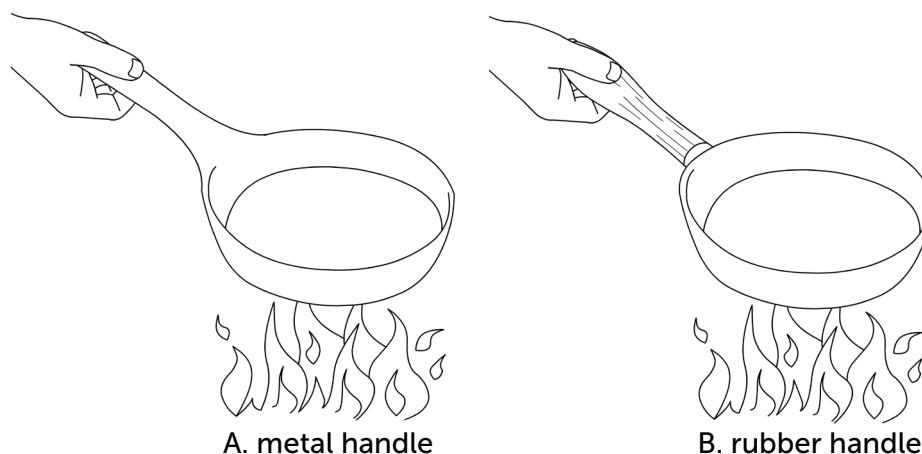
## Results

How is the temperature difference related to the thermal conductivity ( $k$ )? Explain your reasoning for this.

A greater temperature difference means the thermal conductivity ( $k$ ) is less. The heat transfer rate is smaller, so the outer thermometer temperature is closer to the outside air temperature.

## Analysis

The diagrams below show a frying pan over a fire. In each case, indicate which variable in the equation is changed from one drawing to the other, and whether the heat reaching your hand is great for drawing A or drawing B.



In which case, A or B, will the rate of heat reaching your hand be greater?

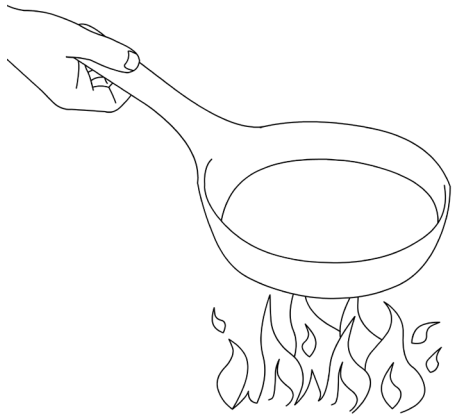
A

Which variable in the equation is being changed?

More layers or lower thermal conductivity

Describe an everyday situation where you have directly experienced the difference in conductivity between two materials.

Answers will vary. Here are few examples: Metal vs. wood pot handle, Touching metal versus cloth when all are at the same temperature; Holding a hot drink in styrofoam cup vs. plastic or paper cup.



A. hand farther up the handle



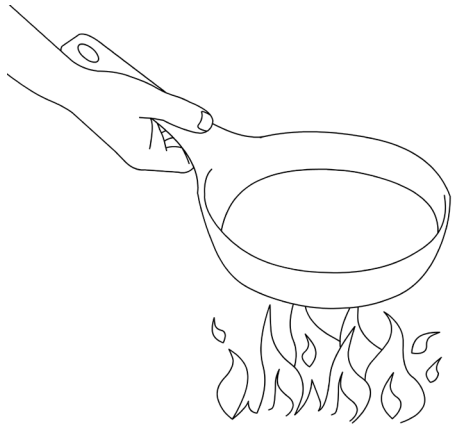
B. hand closer to the pan

In which case, A or B, will the rate of heat reaching your hand be greater?

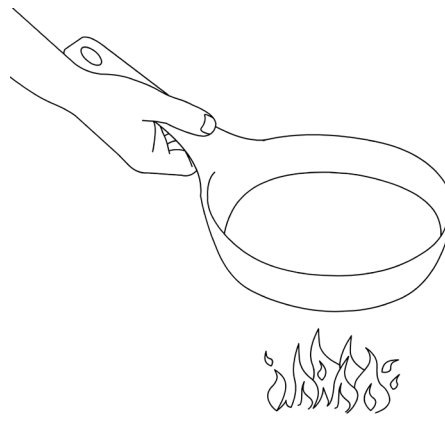
B

Which variable in the equation is being changed?

Wall thickness  $L$



A. more intense heat source



B. less intense heat source

In which case, A or B, will the rate of heat reaching your hand be greater?

A

Which variable in the equation is being changed?

Temperature difference  $\Delta T$

# Connection to buildings

## Background

In the building trades, the rate of heat loss is called conductivity (U), which is the same as k, seen on page 31. The most common measure of conductivity is its inverse: resistance to heat flow, called R or R-value.

**R (thermal resistivity) = 1 / U (thermal conductivity)**

The greater the value of R, the more slowly heat is lost. Doubling R-value means the rate of heat loss is cut in half.

The American building trades don't use metric units. For instance, heat flow is measured in British Thermal Units (BTU) per hour, instead of kilojoules per second. Temperatures are in Fahrenheit rather than Celsius. Thickness is in inches, and area is in feet instead of meters.

To do real calculations on a building, you must get used to doing lots of conversions of units! This project will focus on the relative behavior of different materials, rather than exact calculations.

R can be given per inch of material or for the whole assembly. For example, many common insulating materials have an R-value of 3 to 5 per inch, in standard American units. Fiberglass in a 5 ½" wood frame wall adds up to about R-20. Insulation in ceilings and roofs, where there's more room for insulation, is commonly R-30 to R-40.

Windows typically have the lowest R-value in the building envelope: R-1 for single glazed, R-2 for double glazed, and R-3 or 4 for triple or specially treated glazing. So the typical wall is five to ten times as insulating as the typical window. But there is five to ten times as much wall area as window area, so the two elements contribute equally to the total heat loss, roughly speaking.

Have a short discussion about the R-value of common building assemblies. Point out that **continuity** of the insulation is incredibly important. Make a list and ask students to put them in order from low R to high R:

- Metals
- Masonry
- Wood
- Solid plastic
- Fiberglass
- Cellulose
- Styrofoam (air-filled foam insulation)
- Isocyanurate, icynene (foam insulation with other gases)
- Fancy high-tech insulations used in space

Windows are about R-1 per layer, but now high-performance windows are arriving that have R-values of 10 or more.

Note that the true insulating value of a wall or ceiling depends very much on the quality of workmanship. Gaps and voids can radically reduce the nominal R-value.

Material	Approximate R-value in US units
2x4 wall with insulation	12
2x6 wall with insulation	20
12" of attic insulation	45
12" masonry or concrete foundation wall	2
Single sheet of glass	1
Insulated glass	2
High-performance insulated glass	3
Insulated door	5

Masonry is surprising. It has a high thermal heat capacity, but its R-value is low. That is, it stores a lot of heat, but it also conducts heat well. An 8" masonry or concrete wall has only as much R-value as a double-glazed window (about R = 2)!

Describe the advantages of a well-insulated house.

It will use less energy to heat in winter and less energy to cool in summer. Also it will be more comfortable because the temperature throughout will be more even and there will be fewer drafts.

Recall that heat loss is proportional to both the thermal conductivity and the area of a surface such as a wall. If a house had ten times as much wall area as it had window area, and the wall was ten times as insulating, what would be the relative heat loss from wall and window?

They would be the same, because the higher conductivity of one balances the greater area of the other.

Why do you think it's common to add so much insulation in the attic (see preceding chart)?

There's usually lots of room in an attic for insulation so it's inexpensive to have 12" or more. Also, since hot air rises, the ceiling is warmer and the air leaks out through a poorly sealed attic.

# Heat Transfer

## Convection

### *Introduction*

Convection is defined as the circulation of fluids (liquids or gases), either natural or forced. Hot or cold fluids can add or remove heat. Natural convection is caused by density differences. Hot air rises because it is less dense than cold air, so air will rise above a heater and sink near a cold window. Forced convection refers to fluids being pushed around by outside forces. A fan or a pump are forms of forced convection, which is very useful for moving heat from one place to another.

In this section you will investigate the effects of convection in a house.

### *Natural convection*

Hot air rises, because it's less dense than cold air. Warm air in a room quickly rises upward, and cold air sinks downward, even if the temperature differences are quite small.

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How do fluids carry heat from one place to another?

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Can air carry heat into and out of a house?

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#### Learning goals

Convection is the flow of fluids carrying heat from one place to another.

Convective heat transfer may be natural (due to density differences between hot and cold fluids) or forced (induced by external forces such as fans or pumps).

Insulating materials are often mostly air that is prevented from moving, that is, convection currents are stopped.

Infiltration is to describe the exchange of air between inside and outside, which can be a major source of heat loss.

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# Natural convection in a cup

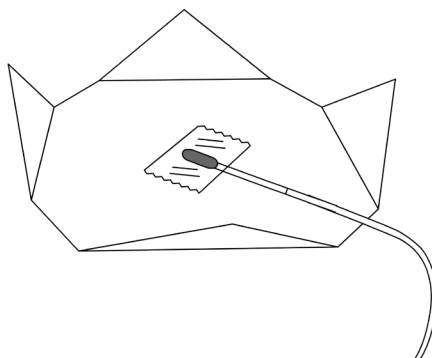
## Tools & materials

- Two fast-response temperature sensors (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensors
- Scissors
- Tape
- Two plastic or Styrofoam cups
- Two pieces of cardstock to cover the cups
- Shallow pan
- Hot water
- Loose insulation such as crumpled paper, foam packing beads, fiberglass, or cellulose, cloth, tissue paper

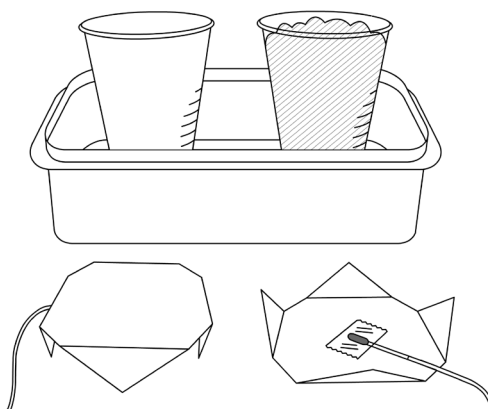
This experiment compares an insulated space to an open air space. Note that any material that inhibits air circulation – tissue paper, cloth, cellulose, packing beads – is worth a try. Although students can't see air circulation, they should be able to describe it in words or draw a diagram.

## Procedure & data collection

1. Cut out two pieces of cardstock slightly larger than the tops of the two cups.
2. Tape the temperature sensors to the undersides and fold over the corners to fit on the cups.

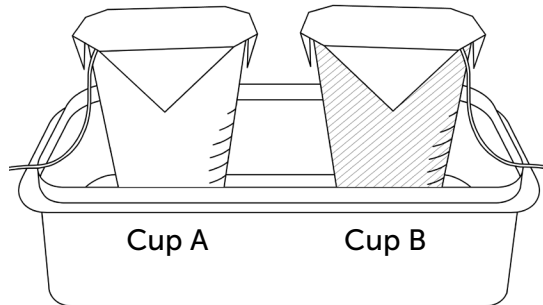


3. Fill one cup with loose insulation. Leave the other cup empty.
4. Place the cups in a shallow pan.





- Place the cards on top with the temperature sensors on the lower side.



- Connect the temperature sensors.
- Start data collection. Wait for a minute or so until the sensors settle at roughly the same temperature.
- Add a small amount of hot water to the pan. If you add too much, the cups will start floating.
- Note the changes in temperature of the two sensors.
- Stop data collection about 30 seconds after you add hot water.
- Record the temperature changes in 30 seconds in the table below.
- Save your Logger Lite file

Convection in two cups		
	Empty cup A temperature	Insulated cup B temperature
Before hot water		
After 30 seconds		
Change in temperature	_____ °C	_____ °C

## Results

Which temperature changed most quickly, the empty cup or the filled cup?

For each cup, about how long did it take for there to be a noticeable difference?

## Analysis

Explain how the heat moves from the hot water to the sensor in each case. Draw a diagram of the air flow in each case.

Air heated at the base rises, displacing the colder air at the top, which sinks and is heated and rises in turn.

Give an example where heat is transferred by convection in a house.

warm ceiling; cold floor; warmer upstairs than downstairs; heat rising from a radiator or baseboard heater (no blower); hot gases going up a chimney; water circulating in a pan on a stove

# Stopping convection

This experiment is optional but should be quick and more creative than the previous one.

## Introduction

How else could you control convection? For instance, what would be the effect of adding a “ceiling” – a single horizontal circle of paper halfway up the cup? Would this be as effective as insulation throughout the space? What about two or more “ceilings”? What about vertical walls inside the cup?

### Procedure & data collection

1. Pick two “convection-stopper” designs that would stop convection, using just paper and tape. Use as little material as possible.
2. Install your designs in the two cups.
3. Place the two cups in a shallow pan as before.
4. Place the cards with temperature sensors attached on top of the cups.
5. Start data collection and wait for a minute or so until the sensors settle at roughly the same temperature.
6. Add a small amount of hot water to the pan.
7. Stop data collection about 30 seconds later.
8. Record the temperature changes in 30 seconds in the table below.

Stopping convection		
	Cup A	Cup B
Before water is added		
After 30 seconds		
Change in temperature	_____ °C	_____ °C

## Results

Describe your "convection-stopper" designs.

Cup A design:

Cup B design:

Compare the arrangements in the table below.

Convection in cups comparison	
Arrangement	Temperature change
Empty cup	
Insulated cup	
Cup A design	
Cup B design	

Explain your results, using diagrams to show how you think the air is moving inside the cup.

## Forced convection

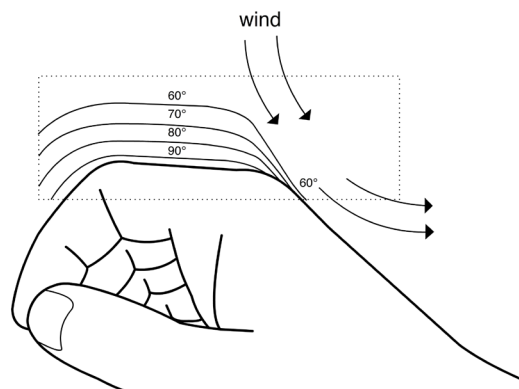
Forced convection refers to motion of a fluid that is not caused by differences in density between warm and cold (“hot air rises”). A fan (air) or a pump (water) is an example of forced convection. It is a very useful way to move heat around. For example, hot-air heating and air conditioning systems use large ducts to transport warm or cold air around a building.

Water can also carry heat from one place to another by being pumped through pipes, that is, by forced convection. The great advantage of water is its enormous specific heat. Large amounts of heat can be transported from the boiler to all corners of the building. It is then transferred to the air in various ways.

Wind chill describes the cooling effect of moving air across a warm surface, such as our skin. The cause of wind chill is simple, and it depends on the difference between conduction and convection. Air is a very good insulator, if it doesn’t move. Most good insulators – wool, foam, fiberglass – trap air in tiny pockets so that it can’t circulate. Heat conducts very slowly across each little air pocket.

On the other hand, air moves very easily in larger spaces, driven by even the slightest temperature differences. When it moves, warm air carries heat from one place to another. Large air spaces in walls are not good insulation because the air moves freely and carries heat from one side to the other.

Picture a hot surface (such as your skin) with cold air above it. Right next to the surface is a thin layer of still air that provides some insulating value because it is not moving. Imagine what happens when you turn on a fan. Your skin cools off because the still air layer is stripped away, and the skin surface is directly exposed to the cold air.



Be sure all students understand that moving air is not inherently colder than still air. “Wind chill” is due to a temperature difference (air that is colder than our skin) and the stripping away of the thin insulating surface layer of still air next to our skin.

Discussion question: why does putting our hand in hot or cold water feel so much hotter or colder than air of the same temperature?

Answer: The water has a much higher heat capacity, so it warms or cools the skin much more quickly by carrying more heat.

## Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Metal ruler (cm)
- Scissors
- Safety utility cutter
- Fan (optional)
- Clear tape
- Styrofoam cup filled with hot water
- A piece of cardstock to cover the cup

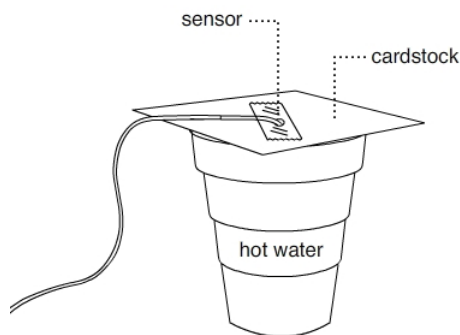
If students don't do the wind chill experiment, have them record what they think would happen and discuss it.

## Wind chill

### Procedure & data collection

In this experiment you will measure the effect of moving air on surface temperature.

1. Start data collection. Hold the sensor in front of the fan and compare room temperature with the fan off and the fan on. Record the two temperatures below.
2. Tape the temperature sensor to a piece of cardstock and tape the card down over a Styrofoam cup of hot water so it won't blow away.



3. Start data collection again. Wait for two minutes or so until the sensor settles at a steady temperature.
4. Turn the fan on while continuing to record temperature. If you don't have a fan, use a piece of cardstock to fan air across the sensor. Don't blow – your breath is not at room temperature!
5. Wait until the temperature is stable again and turn the fan off.
6. Wait until the temperature is stable again and stop data collection.
7. Enter the temperature data in the table below.

Wind chill	
Measurement	Temperature
Room temperature	
Room temperature with fan	
Fan off	
Fan on	
Fan off	
Average difference of fan on vs fan off	

Be sure all students understand that moving air is not inherently colder than still air. "Wind chill" is due to a temperature difference (air that is colder than our skin) and the stripping away of the thin insulating surface layer of still air next to our skin.

Discussion question: why does putting our hand in hot or cold water feel so much hotter or colder than air of the same temperature?

Answer: The water has a **much** higher heat capacity, so it warms or cools the skin much more quickly by carrying more heat.

## Results

Explain your results. Did the fan change room air temperature? Why?

No. The air is moving but that doesn't change its temperature.

Did the fan have an effect on the heated sensor?

Yes. The sensor was closer in temperature to the moving air, because the insulating air layer next the sensor was blown away.

Explain your results in terms of convection.

Convection strips away the heated air and replaces it with cooler room air next to the sensor.

Would wind make a house lose heat faster? Explain.

Yes, for the same reason as above. It might also increase infiltration.

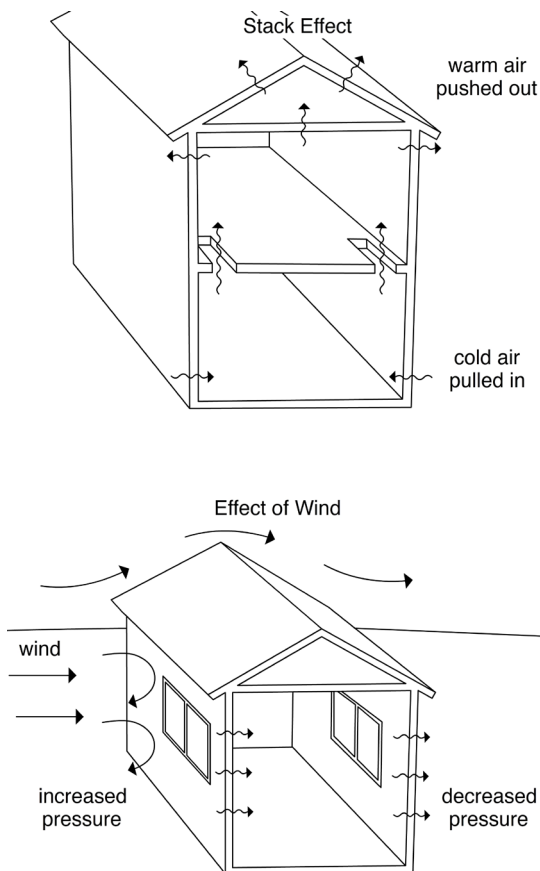


# Infiltration

Infiltration refers to outside air leaking into a house. This implies that inside air is also leaking out (exfiltration), so infiltration is loosely used to describe the exchange of air between inside and outside. If the inside air is warm and the outside air is cold, lots of heat can be lost, the energy bill will increase, and the house will be drafty and uncomfortable.

Infiltration can be driven by two forces: a) the “stack effect” or the “chimney effect,” where rising hot air pushes outward at the top of a building and cold air is drawn inward at the bottom; b) wind, which creates greater pressure on one side of a building than the other, and pushes air through any cracks in the building.

You can explore infiltration further when you test you own model house in the section called “Modify your solar house.”



## Connection to buildings: Convection heat loss

### Application

There are two ways convection might cause a building to lose heat:

1. Hot air leaks out through holes in the building (infiltration driven by the stack effect).
2. Moving air lowers the surface temperature of the building (wind chill effect) and increases the heat loss from the walls and windows. It also enters the building through cracks and holes (infiltration).

Suggest how you might cut down on these forms of heat loss in a real house.

To cut down on infiltration, seal all of the possible holes or cracks in the house – around pipes, outlets, and basement walls. Make tighter windows and doors.

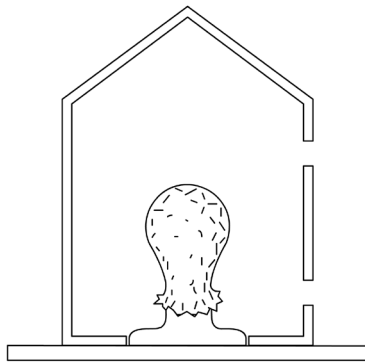
Have you noticed differences in temperature between different rooms or levels in your house, or between the ceiling and the floor? Explain why in terms of conduction and convection.

Different rooms on the same level: Rooms might have the following differences: Different number of windows (conduction), different insulation (conduction) more exposed exterior walls (conduction), sides more exposed to the wind (convection). Different levels: heat would rise and tend to make upper floors warmer. Cold air flows in at the lower levels, being drawn in by convection.

## Summary

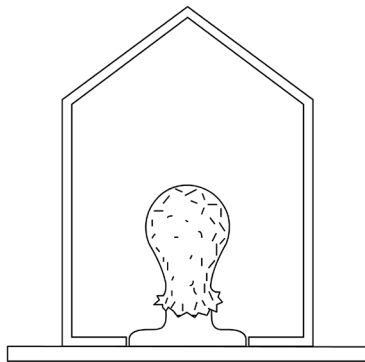
Here is a cross-section of a one-room house. There is a leaky joint near the ceiling and another one near the floor. Suppose the average temperature is  $40\text{ }^{\circ}\text{C}$  inside and  $20\text{ }^{\circ}\text{C}$  outside.

- Draw what you think the heat distribution might be in the house by writing temperature values in five different locations.
- Draw arrows to show what you think the motion of the air might be due to convection.



Now suppose the leaks were sealed up. How would it be different?

- Draw what you think the distribution might be in the house by writing temperature values in five locations.
- Draw arrows to show what you think the motion of the air might be due to convection.

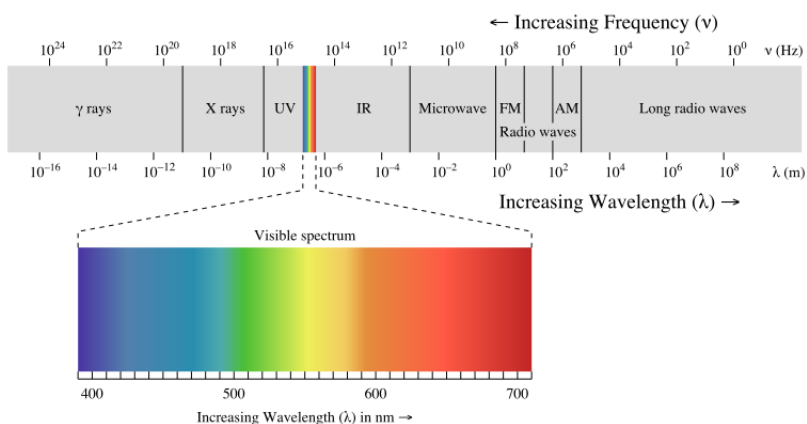


# Heat Transfer Radiation

## Introduction

In this activity you will explore infrared radiation, which you can't see but can feel as heat.

Radiation is the common name for electromagnetic energy traveling through space. It goes very fast (ten times around the earth in one second) and can pass through a vacuum. It doesn't need material to travel in. It has many forms, including visible light, infrared (IR), ultraviolet (UV), X-rays, microwaves, and radio waves. These are all the same form of energy, just with different frequencies and amounts of energy. Different frequencies of radiation interact with matter differently, which makes them seem more different to us than they really are.



*Wikimedia Commons, EM spectrum.svg, Creative Commons Attribution ShareAlike 3.0*

Radiation is not heat. Radiation and heat are two different forms of energy. But one is often transformed into the other in everyday situations. Thermal energy is often transferred by radiation, mostly in the infrared (IR) and visible range. All materials that are warmer than absolute zero ( $-273\text{ }^\circ\text{C}$ ) give off radiation due to the fact that their atoms are vibrating. The amount of radiation is proportional to the fourth power of the temperature ( $T^4$ ), measured from absolute zero. So, the hotter an object, the more radiation it emits.

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Do objects at room temperature give off radiation?

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### Learning goals

Electromagnetic radiation includes visible light but has other invisible forms as well, including infrared radiation.

All objects give off some radiation though not necessarily in the visible spectrum. It increases with increasing temperature.

Different surfaces absorb radiation at different rates.

Radiation energy, when absorbed, is usually converted into heat.

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Note: This is one section of the "Science of Heat Transfer" chapter of the Engineering Energy Efficiency Project. See: <http://concord.org/engineering>

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Also most surfaces absorb radiation and transform it into heat. White surfaces reflect visible light, but absorb infrared. Black surfaces absorb both visible light and infrared. Shiny surfaces reflect both of them.

The fact that all objects give off radiation energy is a little surprising. We usually imagine that only “red hot” materials radiate, because we can’t see other wavelengths that aren’t visible light. This experiment will explore radiation from objects at ordinary temperatures. This radiation is mostly in the infrared range, which is right next to visible light but with longer wavelengths. Note the infrared range on the chart above.

Depending on the level of your students, you may wish to begin this chapter with a brief inquiry into what they understand about electromagnetic radiation. Much of this is not intuitive! For instance,

- Can radiation travel through empty space? Yes, for example, light from the sun.
- Is radiation a form of heat? No, they are two different forms of energy. But hot objects radiate, and absorbed radiation turns into heat.
- Can radiation go through things? Yes, depending on wavelength and materials. For instance, X-rays (short wavelength) and radio waves (long wavelength) can go through solid opaque objects that stop light and IR. Ask for other examples.
- What are “heat rays”? **Radiation is not heat (that is, molecular motion), but it carries energy from one object to another, heating the cooler one and cooling the hotter one, so it seems like a “heat ray.”**
- Can surfaces “attract” radiation? No.
- What happens when radiation strikes a surface? It can be reflected, scattered, absorbed, or transmitted.

#### **A note about aluminum foil**

Misconceptions about foil are common. Students will say it attracts or repels heat. They may think it keeps things cold but not hot. They may say it’s a good insulator.

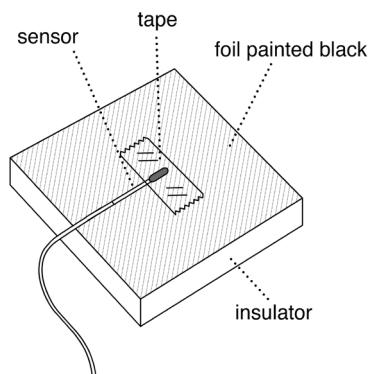
Foil is a **very good conductor**, so it doesn’t stop conduction. But because it’s shiny it does not **emit** IR radiation very much, so there is very little radiative energy loss. It also **reflects** IR, so there is very little radiative energy gain. Therefore, it adds overall insulating value **if it is facing an air space but not if it is touching something**. For example, the foil wrapping the light bulb gets very hot (it’s a good conductor) but doesn’t radiate much IR, so it only heats its surroundings by conduction to the air and subsequent convection of the air inside the model house. An ice cube wrapped in foil reflects IR from the (warmer) surroundings and melts more slowly than a bare ice cube.

# Infrared radiation detection

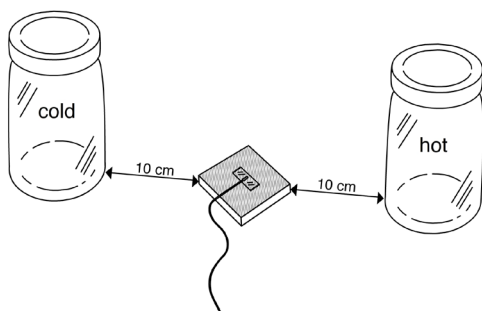
In this experiment you will use a “radiation meter” – a temperature sensor taped to a thin layer of aluminum foil that is glued to a piece of insulation and painted black. Radiation that strikes this surface will be absorbed and will quickly heat up the foil and the sensor. If the sensor temperature is different from the air temperature around it, you have detected heating from radiation.

## Procedure & data collection

1. Tape your temperature sensor to a “radiation meter.” Your teacher will provide this. The clear tape should cover the sensor so that it is held tight against the black surface.



2. Fill a jar with hot water (close to boiling if possible – be careful! You may need cloth or paper towels to pick it up) and another jar with cold water (ice water). The jars should have tops so they won't spill.
3. Place the two jars on a table and the radiation meter between them, with the radiation meter facing upward.



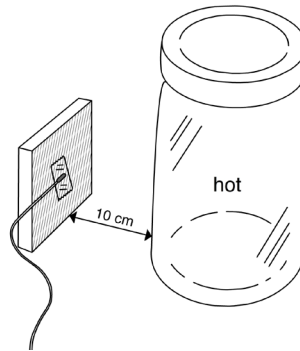
## Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Hot tap water
- “Radiation meter”: foil-faced rigid insulation, about 5 cm square, painted black
- Logger Lite
- USB Flash drive
- Ruler (cm)
- Clear tape
- Hot water jar (plastic or glass)
- Cold water jar (plastic or glass)

This experiment allows students to detect infrared radiation by measuring its heating effect on a low-mass black surface. Three sources of radiation are compared: hot water; cold water; walls of the room (ambient). Expect changes of 1 – 2 °C.

As an extension, measure the transmission of IR by various materials, such as glass, acetate, or clear plastic. Thin black or white plastic is interesting because it stops visible light but transmits IR quite readily. With a hotter source, students could test differences with multiple layers.

5. Start measuring. Let the sensor settle down to room temperature. Be careful not to touch it! If you do, wait until it goes back down to room temperature. It should remain unchanged (to 0.1 °C) for at least ten seconds. Record the room temperature in the table below.
6. Face the sensor toward the hot water jar. It should be 10 cm away. Wait for the sensor to settle down and then record the temperature in the table below. Note: your hands radiate IR too. Keep them away from the front of the meter!



7. Face the sensor toward the cold water jar and repeat the measurement. Record the temperature in the table below.
8. Save your Logger Lite file.
9. Calculate the change from room temperature.

Infrared heating		
Measurement	Temperature °C	Change from room temperature
Room temperature		
Toward hot water		
Toward cold water		

## Results

Summarize your results, which compared the radiation meter facing the room (straight up), the hot jar, and the cold jar.

Could the radiation meter show a different temperature than the air immediately around it? Why?

Yes, if the incoming radiation was different from the room walls.

## Analysis

The radiation meter you used was black so that it would absorb radiation. What if it were white or shiny?

It would not be affected by the surrounding radiation.

If the hot and cold jars influenced the temperature of the radiation meter, how did they do it? Explain in terms of conduction, convection, and radiation. Include specific evidence for your explanation.

The incoming radiation would be greater or less than the outgoing radiation, so the temperature would be different. When the meter faces in different directions, the air around it is the same temperature but the reading changes, so the change is not due to conduction or convection with the air.



Does the cold jar “radiate cold,” or does it “radiate less heat”? Why?

It radiates less. “Cold” is the absence of heat, not a form of negative energy.

Describe a real-world situation where you have felt radiation from something hot and something cold even though they were not visibly hot or cold.

Hot: oven burner, wood stove, radiator, a hot cup (if you don’t touch it)

[Note errors: item either glowing red-hot or heat being transferred by some other means, such as a hair dryer or a hot-air furnace or something you touch]

Cold: window, ice cube

Explain why it is uncomfortable to sit near windows on a cold night even if they are tightly sealed and don’t let cold air in.

The window surface, being at a lower temperature, radiates less IR toward your skin than your skin radiates toward it. Your skin receives less IR than it would from, say, a warm interior wall. So it senses the lack of warmth of the window purely by radiation, independent of cold air that might be circulating from it.

# Connection to buildings

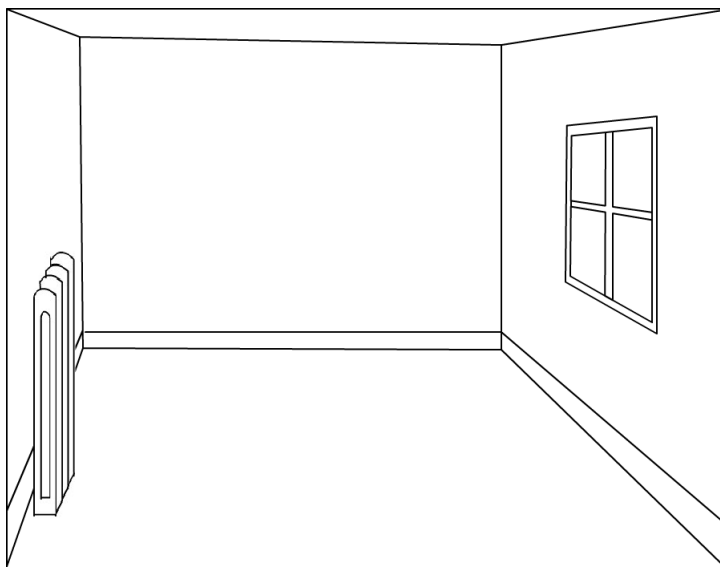
## Application

Passive solar heating consists of letting in sunlight energy (mostly visible light) and stopping heat loss, some of which is IR radiation outward from the warm building. There's a trade-off between the two processes. Larger windows gain more sunlight, but they also lose much more heat than walls. There have been considerable technical advances over the years to make windows that are transparent (let light in), but also have a high insulating value (keep heat in).

For example:

- two layers of glass (three layers in northern climates), with an air space between
- argon gas in the air space, which is less conducting than regular air
- “low-emissivity” coatings on the glass surfaces, which reduces the emission of radiation from the glass itself. If you coated the jar of hot water in this way, the radiation meter would not show a temperature rise when it faced the jar.

Picture a room with large windows on one wall and a steam radiator on the opposite wall. Steam radiators are large cast-iron objects that get very hot — almost too hot to touch. On a cold night, or when the sun is not shining, sketch on the drawing below all of the ways that the heat from the steam radiator and the loss of heat from the windows become distributed throughout the room.



The diagram would show arrows of air rising from the radiator by convection and perhaps making a complete loop in the room. Radiant energy would travel directly across the room to other surfaces in straight lines.

# Heat Transfer

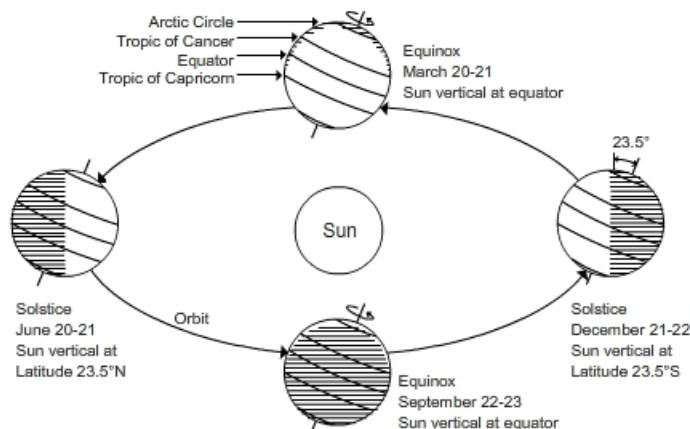
## Energy from the Sun

### Introduction

The sun rises in the east and sets in the west, but its exact path changes over the course of the year, which causes the seasons. In order to use the sun's energy in a building, we need to know where it is in the sky at different times of the year.

There are two ways to think about the sun's path in the sky. One way is to study the tilted Earth traveling around the sun viewed from outer space and figure out where the sun would appear in the sky at your latitude at different times of the day and year. If you have time, give this a try with your class.

Walk around a light source, real or imagined, with a globe that's tilted at the right angle. Turn the globe at different positions (times of the year). Try to picture the length of the day and the angle of the sun.



The other way is to stand on the Earth and plot the path of the sun from your point of view on the ground. This is easier to apply to a building, although, of course, the two ways give the same results.

We will use the earth-centered approach in this workbook.

For this project students must be able to picture the sun's path to design passive solar features in their houses. The focus of this chapter is not the complex geometry of a tilted earth moving around the sun, but simply the path of the sun from the point of view of someone on the earth. Where does it rise and set at different times of the year? How high in the sky is it at noon? How long are the day and night?

### Learning goals

Explain the sun's daily and seasonal path in the sky, in the northern hemisphere at varying latitudes.

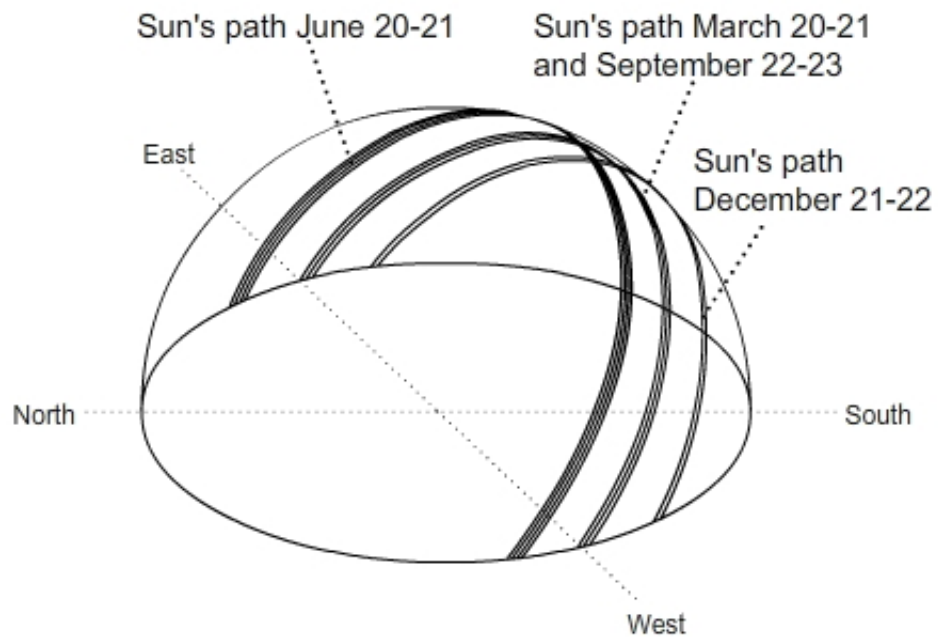
Apply this knowledge to explain how much sunlight energy can be collected using windows, roofs, and other collectors depending on their orientation.

Note: This is one section of the "Science of Heat Transfer" chapter of the Engineering Energy Efficiency Project. See: <http://concord.org/engineering>

Here is a diagram of the sun's path in the sky at different times of the year. It is roughly correct for a northern latitude of 40°. Note the three lines showing the sun's path. One is the summer solstice, one is the spring and fall equinoxes, and one is the winter solstice.

One is the summer solstice (June 21), one is the spring and fall equinoxes (March 20 and September 23), and one is the winter solstice (December 21). The exact dates change a little bit from year to year.

Point out that the winter arc above the horizon is both **lower in the sky and shorter in length (hence time)** than the summer arc. These two key facts explain the seasons.



# Where is the sun?

Learn the basic facts about the sun’s path at your latitude. Use the above diagram, your background knowledge, and class discussion to fill out the following table. Here are some hints.

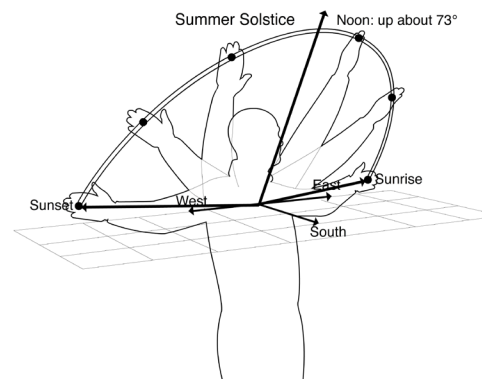
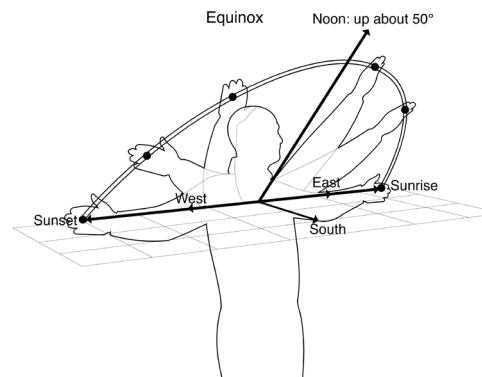
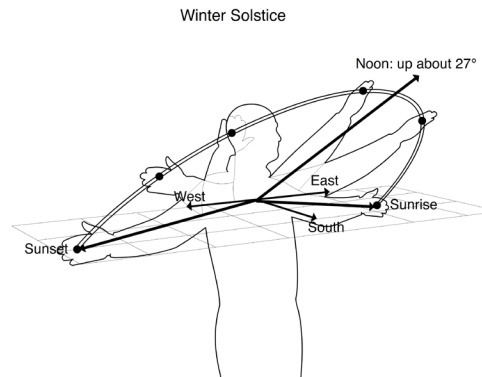
- a) At the equinox at noon, the angle of the sun above the horizon is ( $90^\circ$  minus the latitude). For example, at the equator this is  $90^\circ$ ; at the pole this is  $0^\circ$ .
- b) At the two solstices, the angular height of the sun at noon either increases or decreases by  $23.5^\circ$ – the tilt of the earth’s axis – compared to the equinox.
- c) For the length of the day, do some Internet research. Many sites give the times of sunrise and sunset. (For  $40^\circ\text{N}$ , daylight is about 3 extra hours in summer and 3 fewer hours in winter.)

Chapter 2: Sun’s path throughout the year					
Your latitude: $40^\circ\text{N}$ (Boston, Massachusetts)					
Event	Date	Length of day	Height of sun at noon	Sun rises in what direction?	Sun sets in what direction?
Winter solstice	December 21-22	9 hours	$26\frac{1}{2}^\circ$ ( $50^\circ - 23\frac{1}{2}^\circ$ )	$23\frac{1}{2}^\circ$ south of East	$23\frac{1}{2}^\circ$ south of West
Spring equinox	March 20-21	12 hours	$50^\circ$ ( $90^\circ - \text{latitude}$ )	East	West
Summer solstice	June 20-21	15 hours	$73\frac{1}{2}^\circ$ ( $50^\circ + 23\frac{1}{2}^\circ$ )	$23\frac{1}{2}^\circ$ north of East	$23\frac{1}{2}^\circ$ north of West
Fall equinox	September 22-23	12 hours	$50^\circ$ ( $90^\circ - \text{latitude}$ )	East	West

Fill out this chart together in class or assign it as homework, and then discuss the meaning of the numbers. Do the Sun’s Path Calisthenics with the class (next page). This is the easiest way to show everyone exactly what the sun does all year.

Before you continue, the teacher will lead a discussion on the Sun's Path Calisthenics so that this diagram makes more sense.

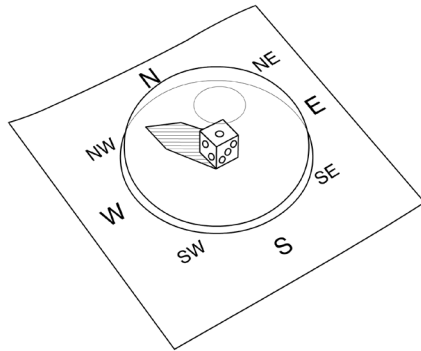
Have everyone stand up and do this exercise.



# Represent the sun's path through the sky

## Procedure & data collection

1. Place the plastic dome lid on a piece of paper.
2. Place a small cube under the center of the dome, as if it were your house.
3. Tape the dome to hold it in place.
4. Draw the directions N, S, E, W around the dome. Then add NE, SE, SW, and NW.



5. Draw the path of the sun in the sky on the dome at the spring equinox, using the marker. Do this by drawing points for the sun's position at sunrise, noon, and sunset at the equinox, using what you recorded on the table above. Estimate the angles, knowing that a right angle is  $90^\circ$ . Then connect the points with a smooth arc.
6. Draw the path of the sun in the sky at the summer solstice, the winter solstice, and the fall equinox, using the same procedure.

## Tools & materials

- Clear dome lid from soft drink or ice cream cup
- Clear tape
- Marker
- Die or small cube
- Piece of white paper

The dome lid may seem a bit childish, but it is the easiest way for students to draw an actual sun's path diagram. Each team should do at least one. If they feel adventurous, they can draw others for different latitudes.

## Analysis

The sun always travels at the same speed across the sky ( $15^\circ$  per hour). If that's true, why does the length of the day change from summer to winter?

The length of the arc when the sun is above the horizon changes with the seasons.

How would the path on the dome lid appear if you were on the equator?

At the Equator, it would be a half-circle directly overhead at the equinox, moving slightly north and south at the solstices.

How would the path on the dome lid appear if you were at the North Pole?

At the North Pole, it would be a circle just above or below the horizon. It would be right at the horizon at the equinox.

Based on your sun's path diagram, explain why it's warmer in summer than in winter when you are not near the equator.

There are two primary reasons: 1) the sun is higher in the sky in summer, so the intensity of sunlight per unit area of the earth's surface is greater; 2) the length of the day is greater, so more heat is received.



# Solar radiation through windows

Now that you know the path of the sun in the sky at different times of year, how can you use this information to use solar energy for heating your house?

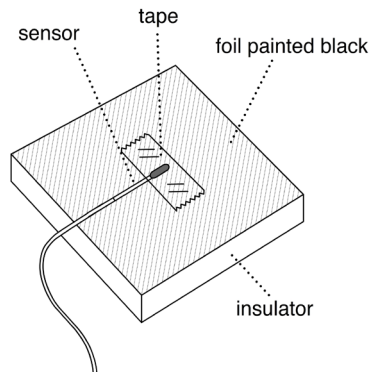
The simplest form of solar space heating is windows that face the sun. Sunlight passes through the windows and is absorbed by surfaces within the house. There are no moving parts and no mechanical systems. **This is called passive solar heating.**

In this experiment you will investigate the best orientation for windows for passive solar heating by measuring how much the radiation meter is heated up by the gooseneck light at different orientations.

## Procedure & data collection

### Part I: Winter

1. Tape your temperature sensor to a "radiation meter." The clear tape should cover the sensor so that it is held tight against the black surface.



2. Place the radiation meter on a table facing straight up.
3. Use the sun angle template (page 11) to position the sun light bulb 20 cm away from the radiation meter at the winter sun angle. Picture the direction of the light as being south at noon in the winter.
4. Connect the temperature sensor to your computer.
5. Turn on the light and start collecting data.

## Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- "Radiation meter": foil-faced rigid insulation, about 5 cm square, painted black
- One 150-300 W light bulb in a gooseneck fixture (note: this will exceed the fixture's wattage rating, but it's on for a short time.)
- Sun angle template

This experiment drives home the importance of angle with respect to the sun for heating. It also shows the difference between summer and winter sun. A common design error is to put in lots of skylights, which aren't good collectors in winter and overheat in summer. This experiment illustrates that with a horizontal orientation. If you skip the experiment, have students theorize about the results and fill out page 9.

6. Every 30 seconds, change the angle of the radiation meter, in the following sequence:
7. In 30 seconds, the temperature will approach a new value but not quite stop changing. After you have finished the sequence, stop collecting data and write down the temperature for each orientation at the end of its 30 seconds.
8. Save your data.

Winter sun angle		
Time	Orientation of radiation meter	Ending temperature
0-30 s	Horizontal	
30-60 s	Vertical facing NORTH	
60-120 s	Vertical facing EAST	
120-180 s	Vertical facing SOUTH	
180-240 s	Perpendicular to light rays	

#### Part II: Summer

9. Connect the temperature sensor to your computer.
10. Reposition the sun light bulb to the summer test angle, using the sun angle template. Repeat the sequence and fill out the following table.

Summer sun angle		
Time	Orientation of radiation meter	Ending temperature
0-30 s	Horizontal	
30-60 s	Vertical facing NORTH	
60-120 s	Vertical facing EAST	
120-180 s	Vertical facing SOUTH	
180-240 s	Perpendicular to light rays	

## Results

Compare winter and summer by filling out the following table. Rank the various orientations from most to least solar heating.

Summer vs. winter solar heating		
Solar heating	Orientation (winter)	Orientation (summer)
5 (most)		
4		
3		
2		
1 (least)		

What is the best orientation for windows so that a building will gain heat in the winter but not in the summer?

South vertical or slightly sloped.  
Also east and west, but less so.

Explain a strategy for using shades or overhangs to control winter heat loss and summer heat gain.

Overhangs can cut down solar gain when the sun is high (summer) but allow it when the sun is low (winter), for south-facing windows.

What are the advantages and the drawbacks of passive solar heating?

The main advantage is free energy. The main drawback is that sunlight is available only during the day, is interrupted by clouds, and is less available during the winter heating season. (That's why it's colder!) Also, passive solar heating requires large windows, which lose more heat than walls. So passive solar heating can cause large temperature swings in a building unless thermal storage is provided.

## Summary

Think about a house you'd like to design. What directions and slopes (vertical, sloped, horizontal) would you choose for large windows? What directions and slopes would you choose for smaller windows? Why?

Vertical south-facing glass has good heat gain in winter and low heat gain in summer.

Sloped south-facing glass has slightly better heat gain in winter but much greater heat gain in summer.

Horizontal glass has modest heat gain in winter and very high heat gain in summer – generally not desirable!

East and west-facing glass has modest heat gain in winter and fairly high heat gain in summer that is hard to shade because the sun spends a lot of time at low angles in those directions in the summer.

Smaller windows to the east, west, and north are generally good to let in some natural light but not cause overheating or excessive heat loss.

CUT OUT THE QUARTER-CIRCLE  
& GLUE IT TO CARDSTOCK

