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.

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

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.

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.

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?

Heat Transfer

Thermal energy

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Heat storage

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

$$Q = c_p m \Delta T$$

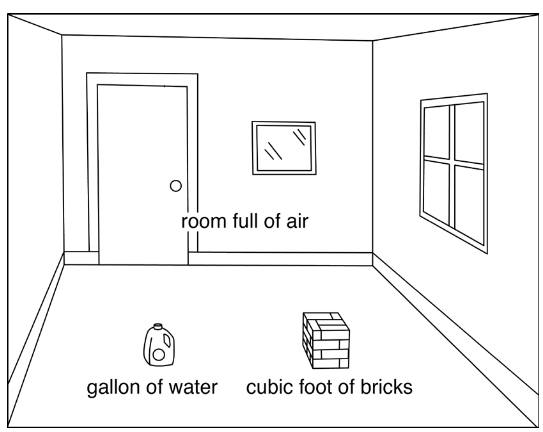
Q = heat (kJ)
c_p = specific heat (kJ/kg K)
m = mass (kg)
ΔT = change in temperature of the material (degrees Kelvin (K), or degrees Celsius (°C))

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 (ΔT) 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.



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.

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

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_0 =	T_f =

Analysis

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

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

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

Your finding: C_{oil} / C_{water} = ________________

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

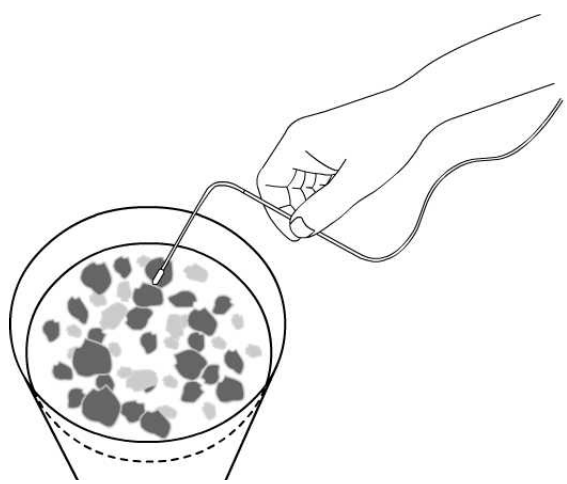
Since C_{water} is 4.18 J/g°C, what is C_{oil}? ___________

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,

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

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

Your finding: C_{test} / C_{water} = ________________

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

Since C_{water} is 4.18 J/g°C, what is C_{test}? ____________

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)?

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.

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

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.

How does heat flow through solids?

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)
ΔT = temperature difference across the material
L = thickness of the layer (m)
A = area of the material (m^2)
k = thermal conductivity of the material per unit thickness (kJ/m/s/°C)

The symbol Δ (delta) means "change in." It could also be written as follows:

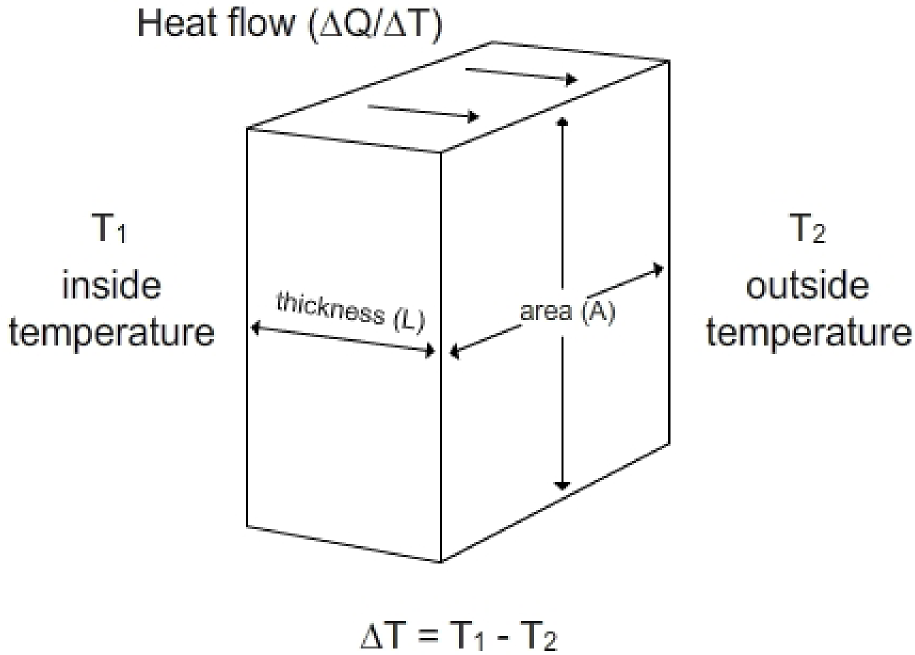
$$\Delta Q/\Delta t = (Q_2 - Q_1)/(t_2 - t_1)$$

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

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 ΔQ .

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

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



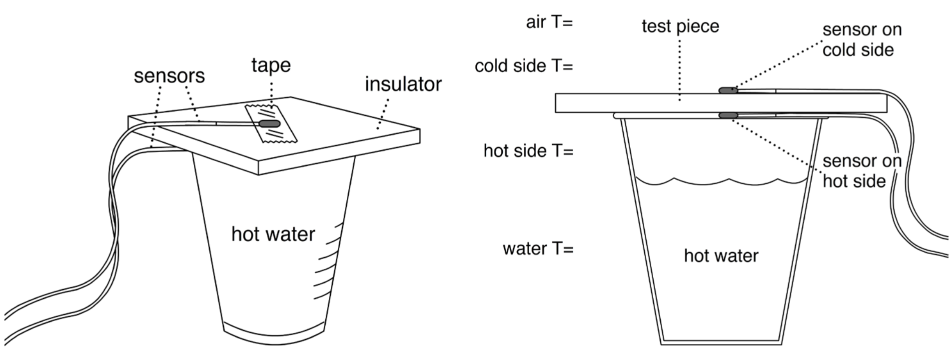
Factors that affect heat conduction through a solid material.

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.

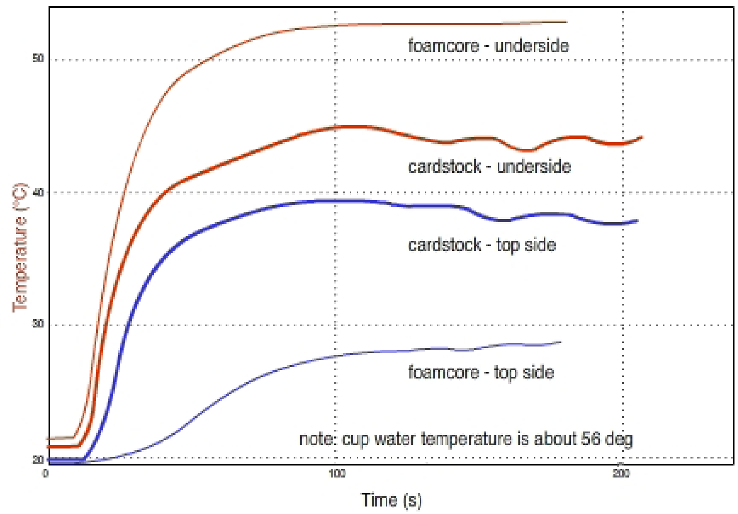


6. Place the material on top of the cup and hold it firmly in place, touching only the edges.
7. Observe the temperature graphs. After they stop changing very quickly (about three minutes), stop data collection and scale the graph.
8. Write down the steady state temperatures in Table 1.

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

9. 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.



10. Save your data file.

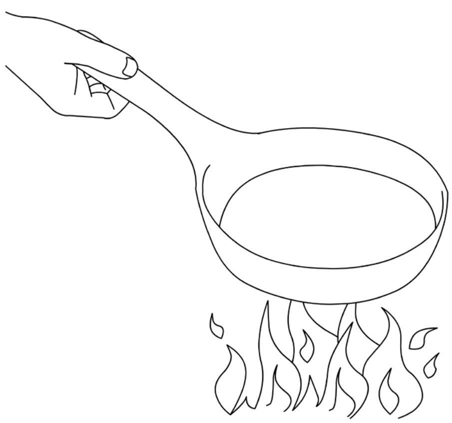
Conductivity of materials					
Material	Water temperature	Air temperature	Inside surface temperature	Outside surface temperature	Difference across material
Initial conditions					
Aluminum					
Cardstock					
Foamcore					

Results

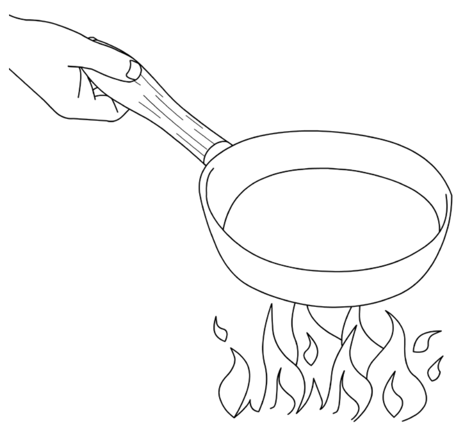
How is the temperature difference related to the thermal conductivity (k)? Explain your reasoning for this.

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.



A. metal handle

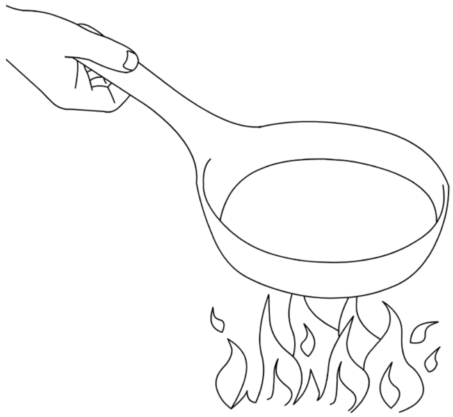


B. rubber handle

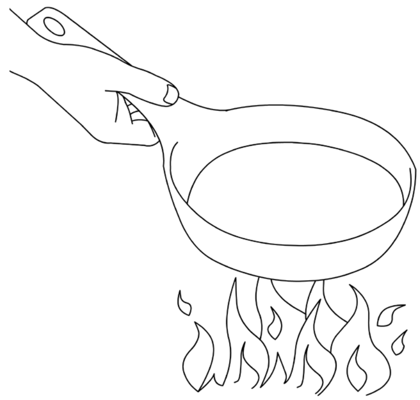
In which case, A or B, will the rate of heat reaching your hand be greater?

Which variable in the equation is being changed?

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



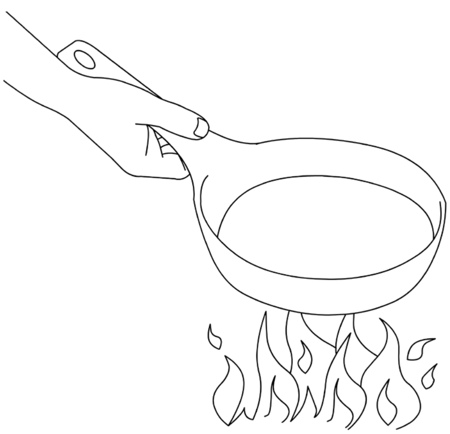
A. hand farther up the handle



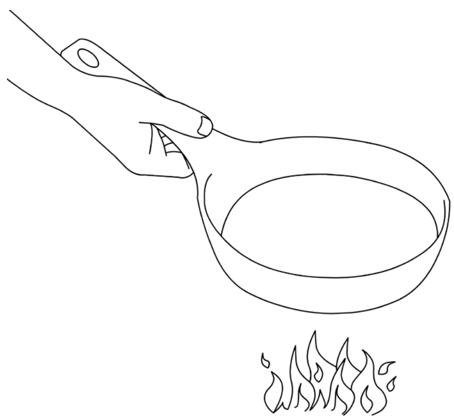
B. hand closer to the pan

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

Which variable in the equation is being changed?



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?

Which variable in the equation is being changed?

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.

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.

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?

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

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.

How do fluids carry heat from one place to another?

Can air carry heat into and out of 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.

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

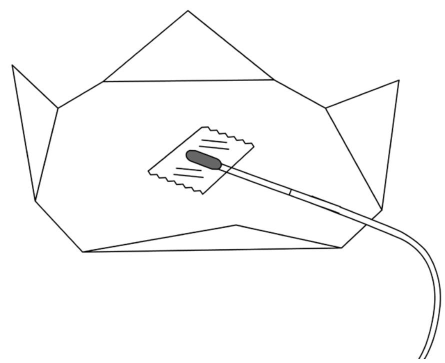
Natural convection in a cup

Tools & materials

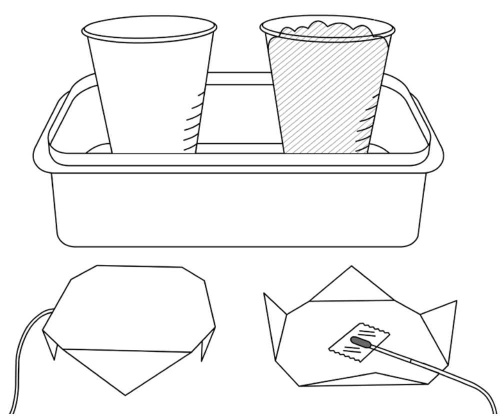
- Two fast-response temperature sensors (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensors
- Scissors
- Tape
- Two plastic or Styrofoam cups
- Two pieces of cardstock to cover the cups
- Shallow pan
- Hot water
- Loose insulation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

Procedure & data collection

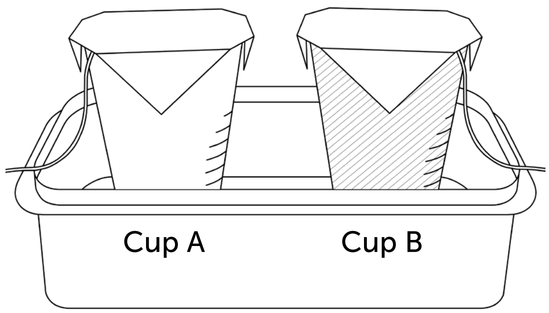
1. Cut out two pieces of cardstock slightly larger than the tops of the two cups.
2. Tape the temperature sensors to the undersides and fold over the corners to fit on the cups.



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



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



6. Connect the temperature sensors.
7. Start data collection. Wait for a minute or so until the sensors settle at roughly the same temperature.
8. Add a small amount of hot water to the pan. If you add too much, the cups will start floating.
9. Note the changes in temperature of the two sensors.
10. Stop data collection about 30 seconds after you add hot water.
11. Record the temperature changes in 30 seconds in the table below.
12. 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.

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

Stopping convection

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

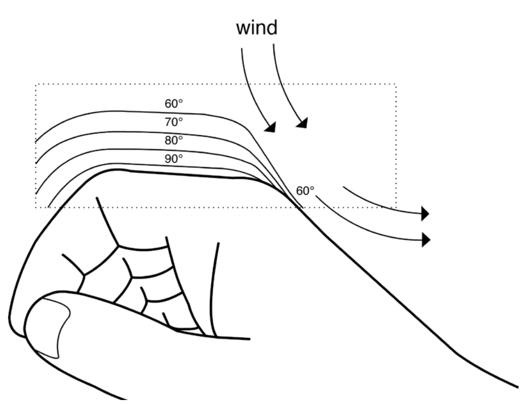
Forced convection refers to motion of a fluid that is not caused by differences in density between warm and cold ("hot air rises"). A fan (air) or a pump (water) is an example of forced convection. It is a very useful way to move heat around. For example, hot-air heating and air conditioning systems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



Wind chill

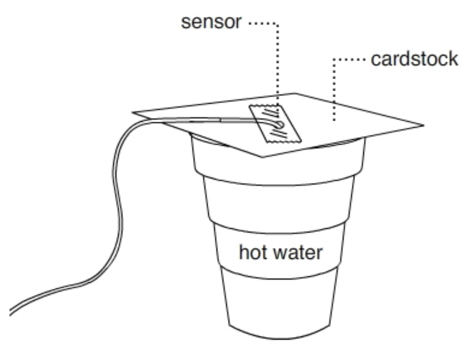
Tools & materials

- 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

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	

Results

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

Did the fan have an effect on the heated sensor?

Explain your results in terms of convection.

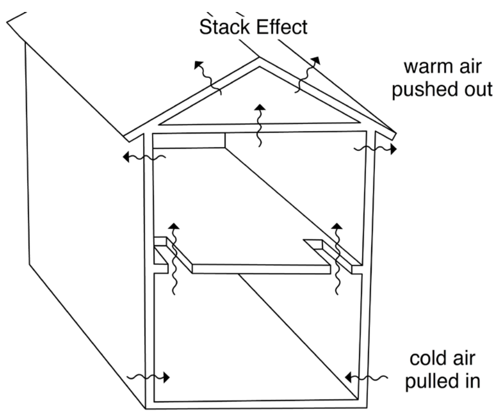
Would wind make a house lose heat faster? Explain.

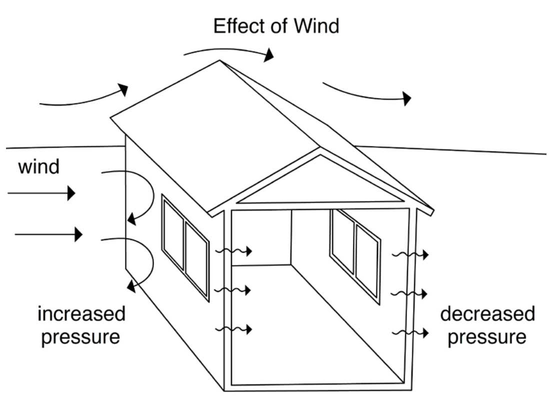
Infiltration

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).

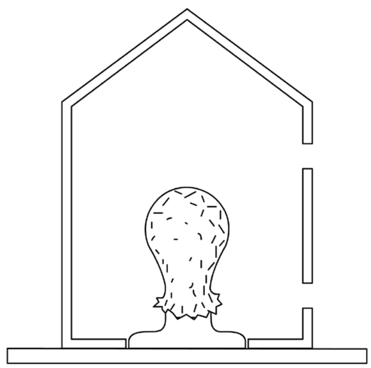
Suggest how you might cut down on these forms of heat loss in a real house.

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.

Summary

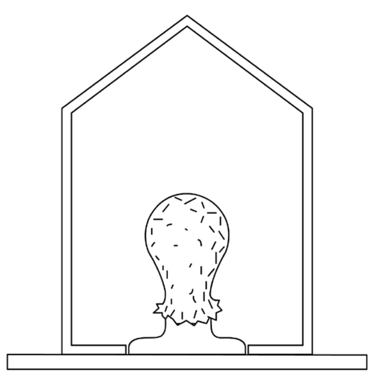
Here is a cross-section of a one-room house. There is a leaky joint near the ceiling and another one near the floor. Suppose the average temperature is 40 °C inside and 20 °C outside.

- 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

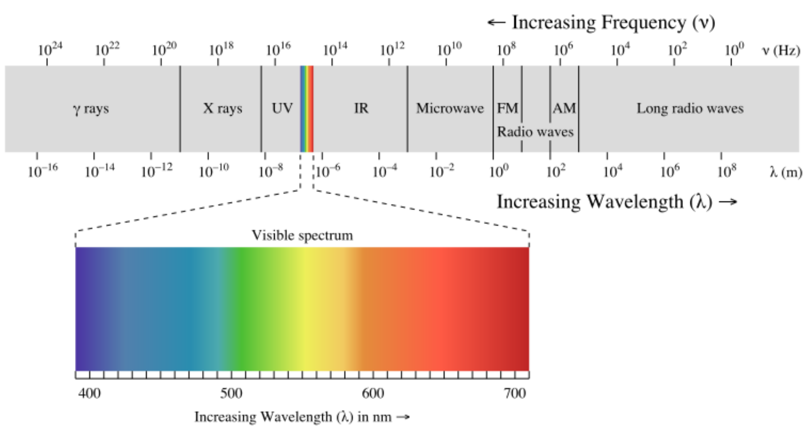
Radiation

Introduction

Do objects at room temperature give off radiation?

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 °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.

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

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.

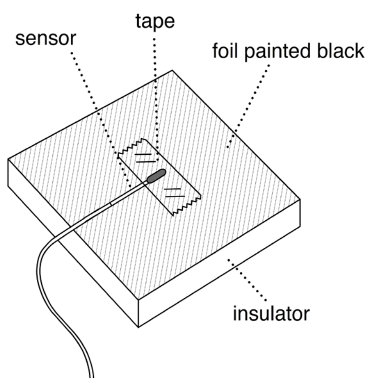
The fact that all objects give off radiation energy is a little surprising. We usually imagine that only “red hot” materials radiate, because we can’t see other wavelengths that aren’t visible light. This experiment will explore radiation from objects at ordinary temperatures. This radiation is mostly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

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.

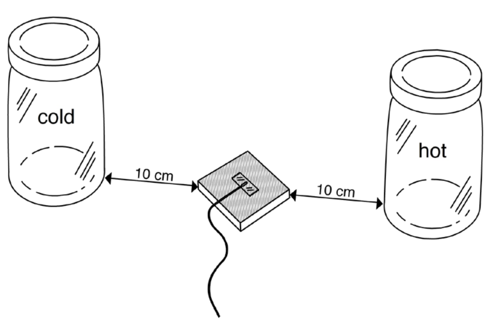
Procedure & data collection

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.

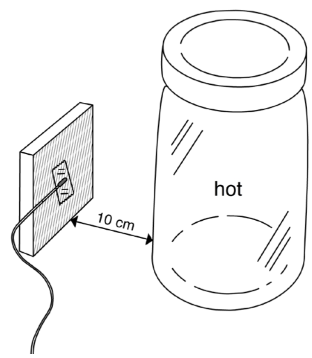


Tools & materials

- 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)

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?

Analysis

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

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.

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

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.

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.

Connection to buildings

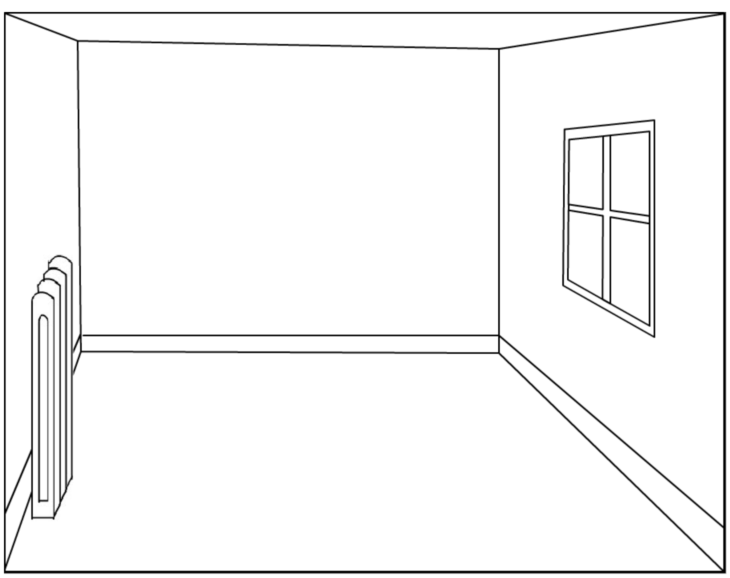
Application

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.



Heat Transfer

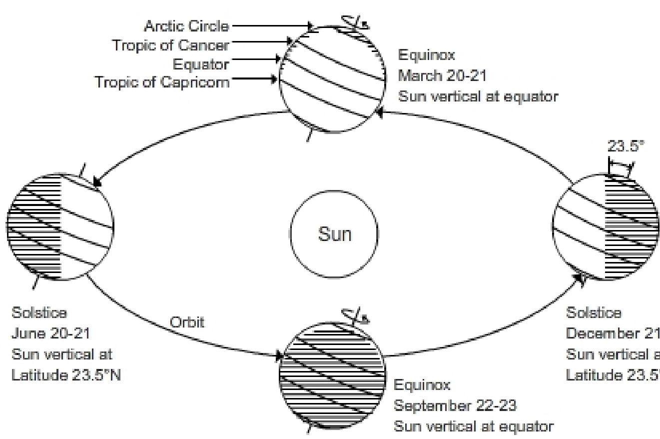
Energy from the Sun

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.



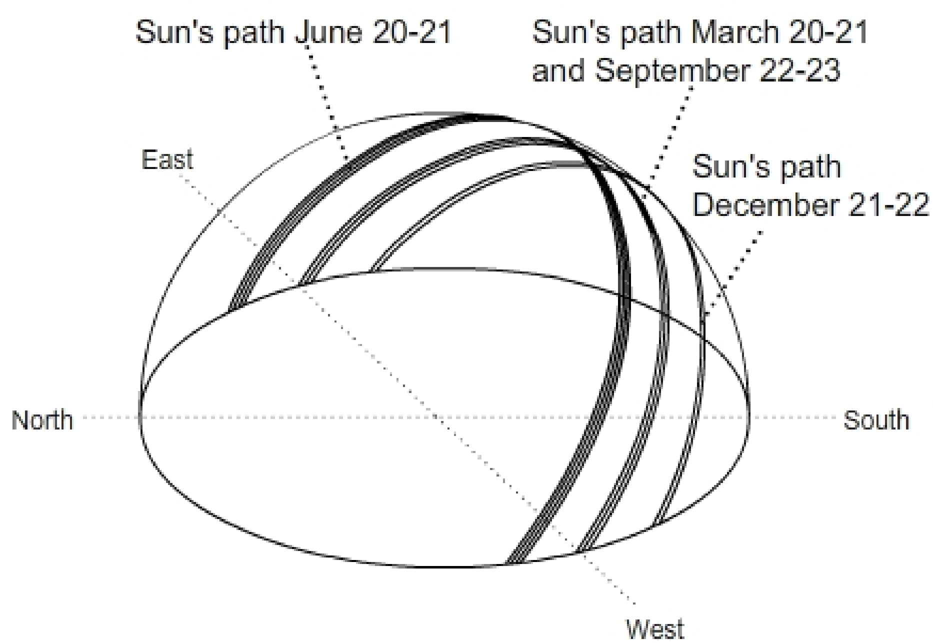
The other way is to stand on the Earth and plot the path of the sun from your point of view on the ground. This is easier to apply to a building, although, of course, the two ways give the same results.

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

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.



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.

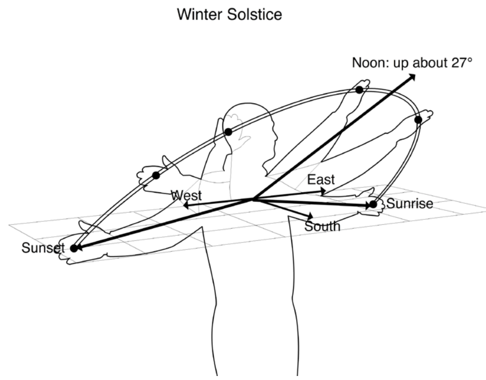
a) At the equinox at noon, the angle of the sun above the horizon is (90° minus the latitude). For example, at the equator this is 90°; at the pole this is 0°.

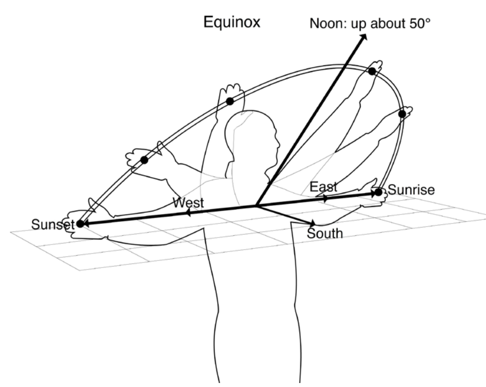
b) At the two solstices, the angular height of the sun at noon either increases or decreases by 23.5°– the tilt of the earth's axis – compared to the equinox.

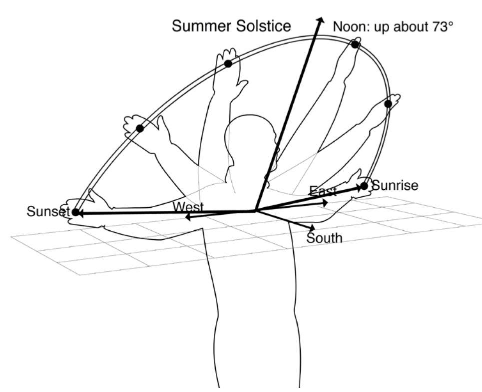
c) For the length of the day, do some Internet research. Many sites give the times of sunrise and sunset. (For 40°N, daylight is about 3 extra hours in summer and 3 fewer hours in winter.)

Sun's path throughout the year					
Your latitude:					
Event	Date	Length of day	Height of sun at noon	Sun rises in what direction?	Sun sets in what direction?
Winter solstice					
Spring equinox					
Summer solstice					
Fall equinox					

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



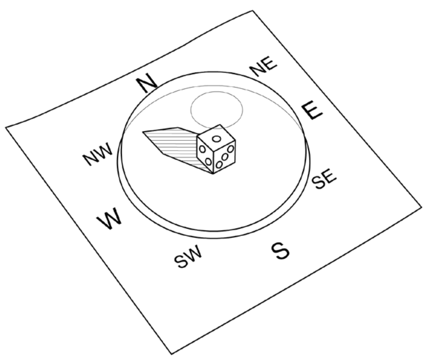




Represent the sun's path through the sky

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°. 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

Analysis

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

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

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

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

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.

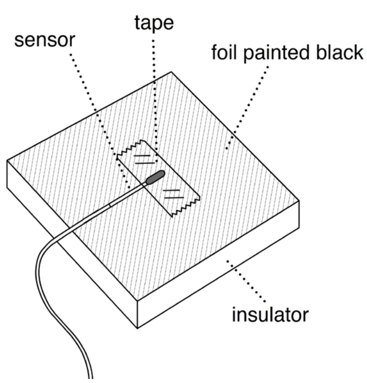
Tools & materials

- 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

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.

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?

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

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

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?

CUT OUT THE QUARTER-CIRCLE
& GLUE IT TO CARDSTOCK