Build and Test a Model Solar House

Introduction

The goal of this engineering project is to construct and test the energy efficiency and solar heat gain of a model house. You will be working with a model rather than a full-sized house, but the principles are the same.

This experiment uses a pre-designed standard house, but you could also build a house of your own design. You could then modify it to improve its energy efficiency and solar heat gain, and test again to see if your modifications were successful.

This project uses a standard procedure for measuring the thermal performance of a house. For the house to lose heat, there must be a temperature difference. The interior must be warmer than the outside. Since you can't cool down your classroom, you will warm up your house to 10 °C above room temperature. This is done with a heater light bulb inside the house.

As with a real house, what matters is how much of the time the furnace must be on to keep the house warm. The more it's on, the more energy is used per day and the greater your heating bill. To imitate this situation, you will record what percentage of time the heater light bulb must be on to keep the house at 10° C above room temperature.

Finally, you will perform the same test, but with a bright light shining on the house, imitating sunshine. You can then tell how much your energy bill is reduced by "solar heating."

Build a model house and measure how much energy is needed to keep it warm.

Goals and objectives

The purpose of this chapter is to acquaint students with the materials, building methods, and measurement procedures they will use throughout the project. It is a "trial run" using a standard house design.

Note: This is the first chapter of a longer engineering project in which students design, construct, and test their own houses (with different shapes, roofs, windows, etc.), using the same simple materials. They also explore the various mechanisms of heat transfer—conduction, convection, radiation, and heat capacity—with hands-on or model-based experiments. See: http://concord.org/engineering

Building Instructions

Tools & materials

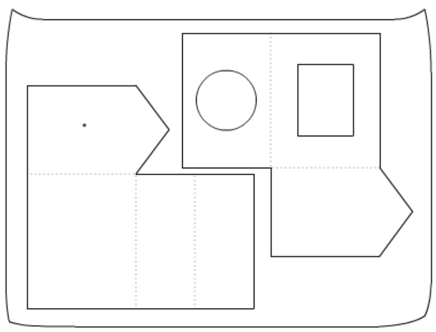
- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Cardstock sheet, 56 x 71 cm (22 x 28 in)
- Acetate sheets for windows
- Cardboard base, about 25 x 35 cm
- Clear tape
- Metal ruler (metric)
- Scissors
- Safety utility cutter
- Pencils
- Cardboard surface to cut on
- One 40 W light bulb heater in a socket with an inline switch, covered with aluminum foil (see page 23, "Fabricating a light bulb heater")
- 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 (see page 25)

Standard House Description

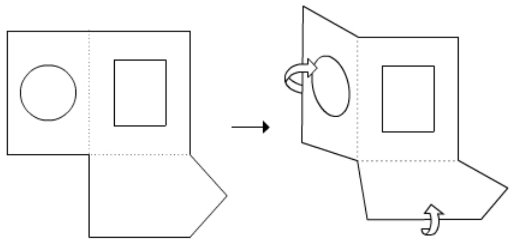
- The standard house has a floor area of 400 cm^2 (16 x 24 cm). It has a window on the south side that faces the sun, and its area is 120 cm^2.
- The house sits on a base that is larger than the house. The base is labeled with the directions north, south, east, and west for testing purposes, so that you can picture the house with a real orientation with respect to the sun*.
- There is enough room inside for the light bulb (15 cm high) and its base. There is a 12 cm diameter hole in the floor for the heater light bulb.

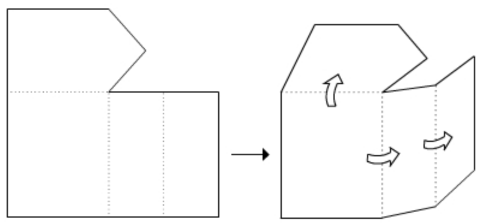
* Note that this project is written for a climate at about 40° north latitude that has warm summers and cold winters. Other climates may have quite different design issues, and the sun's path changes in other latitudes.

1. Draw out the two pieces of the standard house on a piece of card-stock (see pages 26-27 for the exact dimensions). Note how they must be arranged to fit on one sheet. Be sure to mark the location for the sensor - 10 cm from the bottom and in the center of one of the end walls.



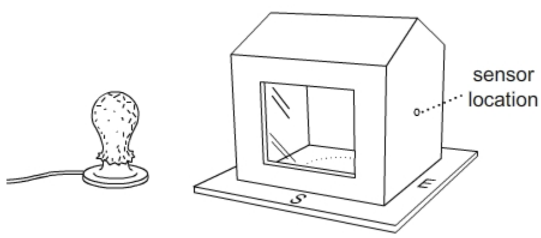
2. Cut out the two pieces, using scissors.
3. Use a sharp pencil to make a hole for inserting a temperature sensor. The hole is 10 cm above the floor.
4. Cut out the window and tape a piece of acetate over it on the side of the cardstock that will be inside the house.
5. Cut a circle out of the bottom of the house, as in the template, so that the heater light bulb can fit in. (The circle happens to be the same size as a CD.)
6. Fold the cardboard along the dashed lines. Use the edge of a table to make straight folds.

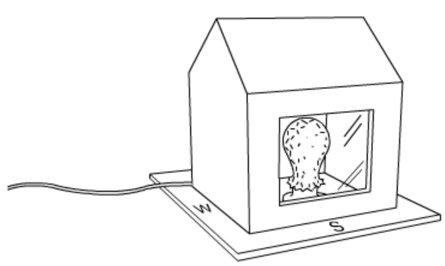




7. Tape the edges together.
8. Label the base with directions: North, South, East, West.
9. Place the heater bulb on the base.
10. Feed the power cord of the bulb through one corner of the house, as in the picture below. Then tape the joints closed around it.

11. Place your house and bulb on the base so that the window faces south and the bulb fits through the hole in the base of the house.
12. Your house will look similar to the house pictured below.





Note the power cord coming out of one corner of the house.

Though the difference between power and energy is straightforward (power is rate, the energy is amount), everyone confuses them. Even experts use the words interchangeably in everyday speech. Furthermore, electrical power is measured in kilowatt-hours, that is, power multiplied by time. It's as if we measured distance in "mph-hours", as in, "It's 180 mph-hours from Boston to New York." Pay special attention to the examples and make sure every student understands that energy (kWh) is how much and power (kW) is how fast.

Background: Power and energy

Energy is a special quality in science and engineering. It has many forms – thermal, kinetic, potential, chemical, electrical, nuclear, and radiation. It can change form, but the total amount of energy remains the same. In other words, energy is not created or destroyed; it just changes form. This principle, called the Conservation of Energy, is central to understanding heat flow.

In simple terms, energy is how much, and power is how fast you use it. A car has a certain amount of energy when going 60 mph, regardless of how quickly it reached that speed. A more powerful engine can get up to that speed more quickly. Energy (Q) is measured in joules. Power (P) determines how fast the heat flows or changes. It is measured in watts, which is the same as joules/second.

$P = Q / t$

Watts (W) = joules (J) / seconds (s)

We can also say that the amount of heat energy is the power multiplied by the time.

$Q = Pt$

Joules (J) = watts (W) * seconds (s)

For example, the power output of a 40 W light bulb is 40 watts. If the bulb is on for one minute it produces 2400 Joules of energy.

2400 J = (40 J / s) (60 s)

In everyday practice, electrical energy is expressed in kilowatt-hours rather than joules.

1 J (1 W-s/J) (1 hr/3600 s) (1 kW/1000 W) = 27.8 x 10^{-6} kWh

1 J = 27.8 x 10^{-6} kWh
1 kWh = 3,600,000 J

As this shows, kilowatt-hours are a more convenient unit because Joules are so small. Also, it's easier to work with hours than with seconds.

What is the power output of a 100 W incandescent bulb?

100 W

How much energy does a 100 W bulb use in 24 hr?

2400 W-hr or 2.4 kWh

How much energy (in kilowatt-hours = 1000 watt-hours) would the bulb use if left on for a year?

2.4 x 365 = 876 kWh

How much energy would you save if you replaced the bulb with a 20 W fluorescent, which has about the same light output but uses less energy? (Fluorescent bulbs are more efficient. For the same power input, they produce more light and less heat than incandescent bulbs.)

4/5 of 876 = 700 kWh
(Or calculate the energy use of a 20 W bulb and take the difference)

How much money would you save if electricity costs $0.15/kWh?

700 x .15 = $105

Background: Celsius vs. Fahrenheit

Note to American students: You will use the Celsius scale for these measurements, so here's a quick exercise to remind you about Celsius vs. Fahrenheit. Fill in Table 1.

$$C = 5/9(F - 32)$$

or

$$F = (9/5)C + 32$$

Celsius vs. Fahrenheit		
	Temperature in °C	Temperature in °F
Water freezes		
Water boils		
Room temperature	20	
A hot day		100

For example, suppose the room temperature is 20 °C. The target temperature for the warmed-up house will be 10 °C higher. What will these temperatures be as measured on the Fahrenheit scale? Fill in Table 2.

Experimental conditions		
	Temperature in °C	Temperature in °F
Room temperature	20	
Target house temperature	20 + 10 = 30	
Outdoor temperature if it were 10 °C below room temperature	20 – 10 = 10	

The last calculation is to show that our experimental conditions have the same temperature difference as a house kept at 20 °C when the outdoor temperature is 10 °C (50 °F). It's a cold day, but not freezing.

Test #1: Keep the house warm

What is the power requirement to keep a house warm on a cold day?

Introduction

Your goal is to warm up your house to 10 °C greater than the air around it. To do this, you will raise the house to the target temperature using the heater light bulb.

As you perform the following steps you will look at the graph generated by a temperature sensor, which will record the time and temperature automatically and represent them graphically.

This project uses a standard procedure for measuring the thermal performance of a house. For the house to lose heat, there must be a temperature difference. The interior of the house must be warmer than the outside. Since you can't cool down your classroom to 0 °C, you will warm up your house to 10 °C above room temperature. This is done with a heater light bulb inside the standard house.

As with a real house, what matters is how long the furnace must be on to keep the house warm. The more it's on, the more energy is used per day and the greater your heating bill. To imitate this situation, you will record what percentage of time the heater light bulb is on.

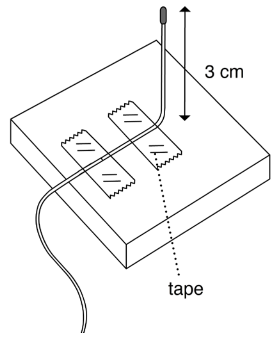
Your goal is to measure how much power it takes to keep your house 10 °C warmer than the air around it. To do this, you will:

- Turn the heater on and off so that the temperature stays within 0.2 °C of the target temperature.
- Record the times when the heater is turned on and off.
- Calculate what percentage of time the heater has to be on to keep the house warm.
- Multiply that percentage by the heater power (40 W) to get the average power supplied to the house.

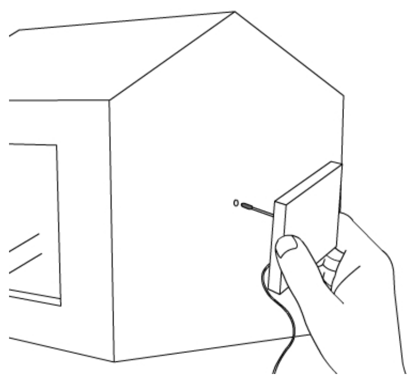
Temperatures in the model houses are very sensitive to position. For consistent results, the sensor must be bent so that it runs straight in and is 3 cm long, as in the diagram. Check every team setup by looking into the house through the window to see that the sensor is not bent up, down, or back toward the wall.

Procedure

1. Cut a 3x3 cm square of cardstock and tape the sensor to the center of it 3 cm from its tip. Fold the sensor 90° so that it is perpendicular to the card and is 3 cm long.

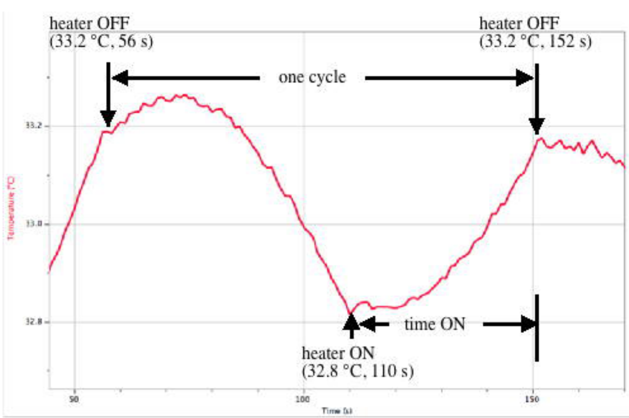


2. Insert the temperature sensor in the hole you made in the middle of the wall of the standard house. The sensor must be pushed through the wall so that it is perpendicular to the wall. Make sure it is not touching the wall. Tape the card to the outside of the house to keep the sensor in place.



Collect data

1. Connect one temperature sensor to your computer. Set up data collection for one reading per second and a total time of 600 seconds.
2. Start collecting data.
3. Touch the end of the sensor to make sure it works. You should see the graph go up.
4. Measure the room temperature and record it in the table below. We will assume it stays reasonably constant throughout the experiment.
5. Calculate your target temperature: about 10 °C above room temperature (round it up to a whole number). Record the target temperature in the table below.
6. Turn the heater on.
7. Start collecting data when the sensor is a few degrees below the target temperature.



8. Refer to the sample graph above, which should look roughly like yours. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A). Note that the data table in Logger Lite makes it easy to note the current time while data is being collected.

   Note: the temperature may continue to rise for a time. That's OK.

This is the basic house heating test. Point out that the students are acting as a "human thermostat." Review how it is analogous to a real house furnace, which turns on and off to keep the house at a constant temperature. The furnace output (power) multiplied by the percentage of time it is on (percent) is the average power requirement to keep the house warm.

Make a table of everyone's results so that they can be compared and discussed.

9. When the sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table below (B).

   Note: the temperature may continue to fall for a time. That's OK.

10. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
11. Stop collecting data.
12. Click the "scale" icon to fit the graph to your data.
13. Save the data file.
14. Calculate the average power requirement to keep the house warm by filling out the rest of the table below.

House heating test	
Room temperature: _____°C	
Target temperature: _____°C	
Upper limit (target temperature + 0.2): _____°C	
Lower limit (target temperature - 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit (point A)	
B. Turn heater ON at lower limit (point B)	
C. Turn heater OFF at upper limit (point C)	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 W * proportion of time heater is on)	_______ W

How to calculate the power requirement (Row G)

Make sure everyone understands how to calculate the power requirement as 40 W multiplied by the percentage of the time the bulb is on.

You used the energy provided by the heater to heat up your house and maintain it at your target temperature. The bulb you used as a heater has a power of 40 W. This means that it releases 40 joules of energy per second. But since it wasn't on all the time, the house used less than 40 W to stay warm. The average power requirement of your house is:

Power requirement = 40 W * time on / total time

Note that the total time should be a full cycle, from OFF to ON to OFF again.

The steps of the calculation are set out in the table above.

Analysis

In your own words, explain the difference between energy and power.

Energy is an amount. Power is the rate of using or transferring that amount.
Energy is how much. Power is how fast.

Which did you measure in this experiment, power or energy?

Keeping warm = power

What are the units for energy? What are the units for power?

Energy: joules or kilowatt-hours
Power: watts or kilowatts

The light bulb in this test house is supposed to model the furnace or boiler in your house. Describe how turning the light bulb on and off is similar to a thermostat in your house.

Like a thermostat, it goes off when the temperature is a bit above the target temperature, and it goes on when the temperature is a bit below, keeping the temperature more or less constant. As with a furnace, one varies the percentage of time the heat is on, rather than the power output of the heater.

How do you think you could reduce the power needed to maintain the house temperature in this model? Explain what you would do and how it would help.

Add insulation or sealing up holes or gaps in the house to reduce the ability for heat to escape. Increase window sizes to the south to collect more solar energy.

Heating your own house

The light bulb in the standard house is like the furnace or boiler in your house. It has a fixed output and is on part of the time. Heating units are sized so that they would be on all of the time only on the coldest days, when there would be the greatest temperature differences between inside and outside, and hence the greatest rate of heat loss. If you improved the energy efficiency of your house, the heater would be on less time and use less total energy over the year.

Your house or apartment has a thermostat, which does exactly what you did by hand in the experiment: it turns the heater on when the house temperature is below the set temperature, and off when the temperature rises above the set temperature. If you graphed the temperature in your house, it would be a wavy line like the graph in this experiment.

In a real house, the yearly energy requirement would be calculated by looking at the energy bill (for example, 400 gallons of oil multiplied by 130,000 BTU/gallon = 52 million BTU = 15,200 kWh).

Note: in the USA, both kilowatt-hours (kWh) and British Thermal Units (BTU) are in common use as heating energy units. If you want to interpret your energy bill and compare electrical energy to oil or gas energy, you will need to convert from one to the other.

1 kWh = 3412 BTU

Look up your actual heating energy use, following the steps below.

Figure out the amount of energy you use for heating. You probably use electricity, oil, or natural gas.

yearly oil (gal) ____________

yearly gas (therms) ____________

yearly electric (kWh) ____________

Make use of the following *approximate* conversion factors:

1 kWh = 3400 BTU

For oil, 1 gallon = 120,000 BTU (allowing for a boiler efficiency of 85%)

For natural gas, 1 Therm = 100,000 BTU

Your annual heating energy use in kWh: ____________

The monthly consumption in summer, multiplied by 12, is deducted to get heating energy use.

If your boiler heats domestic hot water as well as the house, subtract the average monthly summer use from each winter month (about six months in all) to obtain just the heating energy. If heating and hot water are separate, you can skip this step.

Your average monthly hot water energy use in kWh: ____________

Your hot water energy use for 12 months in kWh: ____________

Your heating energy use (annual heating energy minus annual hot water energy) in kWh: ____________

Test #2: Solar Heating Test

Introduction

During the last session you built your house and heated it using a heater light bulb. That situation mirrors the nighttime when there is no sunlight.

Now you will add a very bright light bulb (300 W) outside as the “sun.” Its position will be roughly that of the sun at noon in winter in the northern United States (40° N). You will use a single temperature sensor to measure the house temperature.

You will turn the heater on and off, but leave the sun on all the time. This will simulate a sunny day with light from the 300 W bulb providing “solar energy.”

How does energy provided by the sun reduce the house heating requirement?

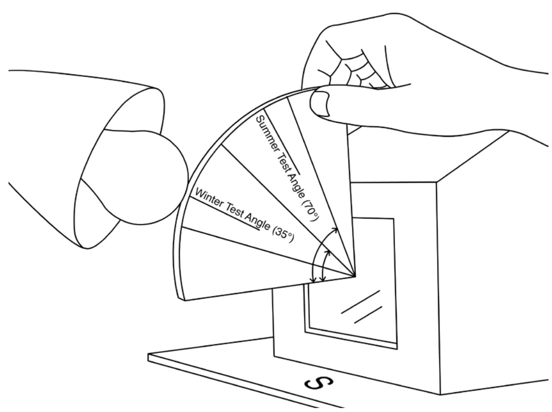
Insist that students be very careful with the light bulbs, turning them off when not in use.

Set up the sensor

Once the room temperature has been measured (page 12), the whole class can use the same value throughout the project unless a large change (more than 2-3 °C) is noticed. Then students don't need to wait for their house to cool down between experiments. This will save considerable time.

Check that every team positions the sun light bulb correctly. Warn them that the gooseneck lamp is tippy.

1. Insert the temperature sensor in the hole at the middle of your house.
2. Connect the temperature sensor to your computer.
3. Set up data collection for one reading per second and a total time of 600 seconds.
4. Use the room temperature from the previous experiment. It will be approximately the same.
5. Calculate the target temperature (room temperature + 10) and enter it in the table below.
6. Set up the gooseneck lamp with a sun light bulb in it, due south of the building.
7. Cut out the sun angle template (see page 25). Place the sun angle template so the corner is in the center of the window.
8. Aim the tip of the light bulb along the "winter test angle" line on the template (see figure below).



Procedure - Collect data

Reminder: the sun bulb stays on; the inside heater bulb is turned on and off to maintain a constant temperature.

1. Switch on the heater light bulb AND the sun light bulb.

NOTE: The 300 W bulb is very hot. Be careful not to touch it, and wait until it cools down to move or store it. Turn it off except while doing the experiment.

2. Start collecting data when the sensor is a few degrees below the target temperature.
3. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A). **Leave the sun on throughout the test.**
4. When the sensor reaches 0.2 °C below the target temperature, turn the heater ON. Record the time in the table below (B).
5. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
6. Stop collecting data.
7. Click the “scale” icon to fit the graph to your data.
8. Save the data file.
9. Calculate the power requirement to keep the house warm by filling out the rest of the table below.

Record student results and in the Chapter 1 Chart "Standard house test ". Discuss the results.

Solar heating test	
Note: Sun is ON for the whole experiment.	
Room temperature: _____°C Target temperature: _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time in seconds (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Power requirement (40 W * proportion of time heater is on)	_______W
H. Average power requirement without the sun (from previous experiment)	_______W
I. Power supplied by the sun	_______W

Analysis

What is the solar contribution to house heating, in watts and as a percentage of the total power requirement?

In a real situation, there might be strong sunshine for six hours a day, on average, out of twenty-four. On the other hand, the light would be much more intense than a 300 W light bulb. What might the solar contribution be in that case?

It would be greater while the sun is shining, but there would be a lot of loss when the sun was not shining. So it's a trade-off.

How might you deal with the problem that larger windows can trap more of the sun's energy when it's shining but also lose more heat when the sun is not shining?

Increase the insulating value of the windows (2-3 layers, low-e coating), add insulating shades that can be closed at night.

Connection to buildings: Solar gain in your own house

This optional exploration encourages students to think about the orientation and possible solar gain of their own house – something they have probably never considered before.

Application

Think about your own house and the possibility of using sunshine for heating it.

a. How many south-facing windows does your house have? Measure the area of each and add them up.

south-facing glass m^2 ___________

b. How good is your south-facing exposure? Are there trees or other buildings that cast shade for part of the day?

c. Could you add more south-facing windows?

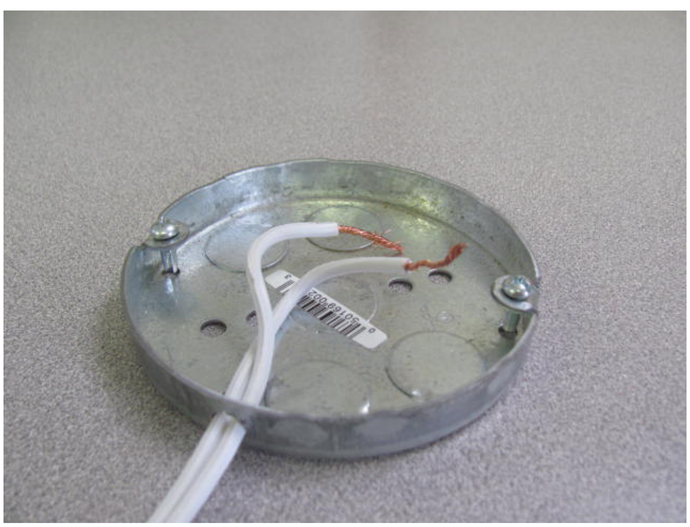
d. What would you do to increase heat gain during sunny periods, but minimize heat loss at night?

Windows with more layers and greater insulation value.
Curtains or shades that seal the windows and cut down heat loss at night.

Fabricating a light bulb heater

Procedure

1. Cut off the outlet end of the extension cord. Strip the wires.
2. Install the inline switch in the extension cord. Note that the common (ground) wire has ribs and the live (hot) wire is smooth. Make sure the switch interrupts the hot wire.
3. Drill a 5/16" (8 mm) hole through the side of the pancake box and insert the cord.

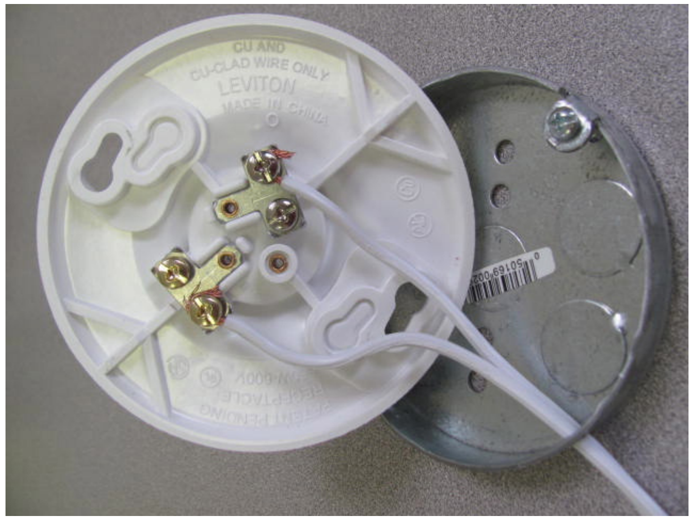


Tools & materials

The required parts, available at any hardware store, are:

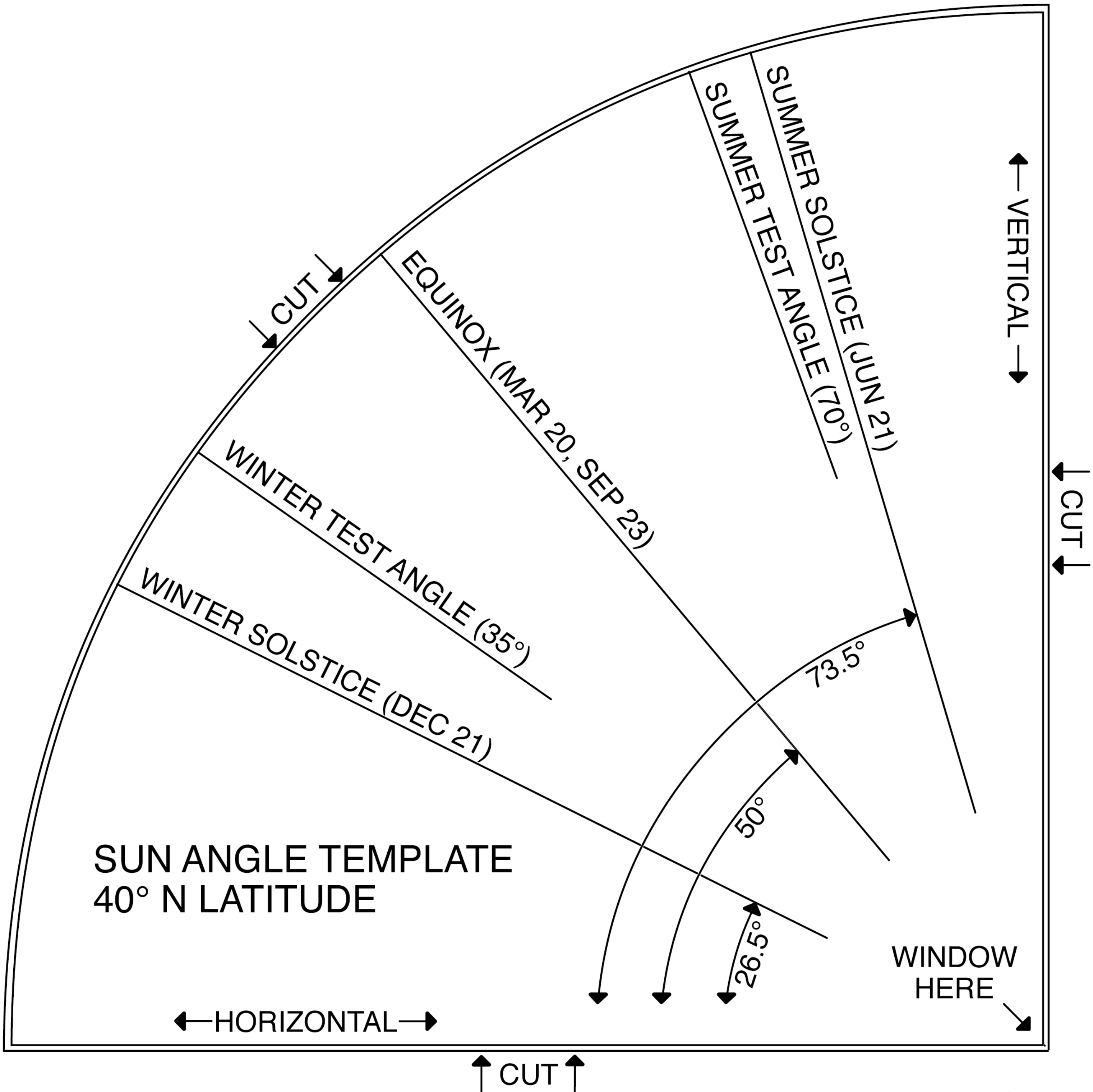
- keyless socket (plastic or ceramic)
- 6' extension cord
- inline switch
- metal pancake box
- 40 W light bulb
- aluminum foil

4. Attach the wires to the keyless socket. The ribbed (ground) wire is attached to a silver screw and the smooth (hot) wire is attached to a brass-colored screw.

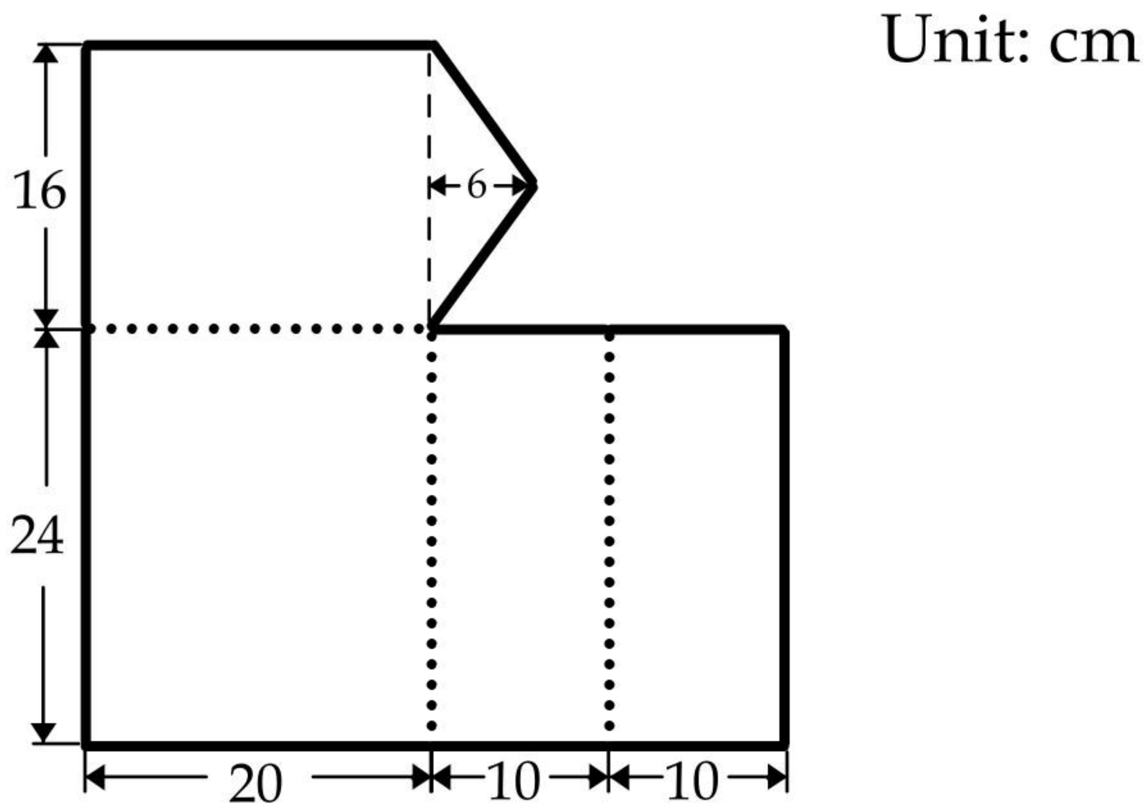


5. Screw the socket to the pancake box. Cover the bulb with a layer of foil to cut down on radiation.

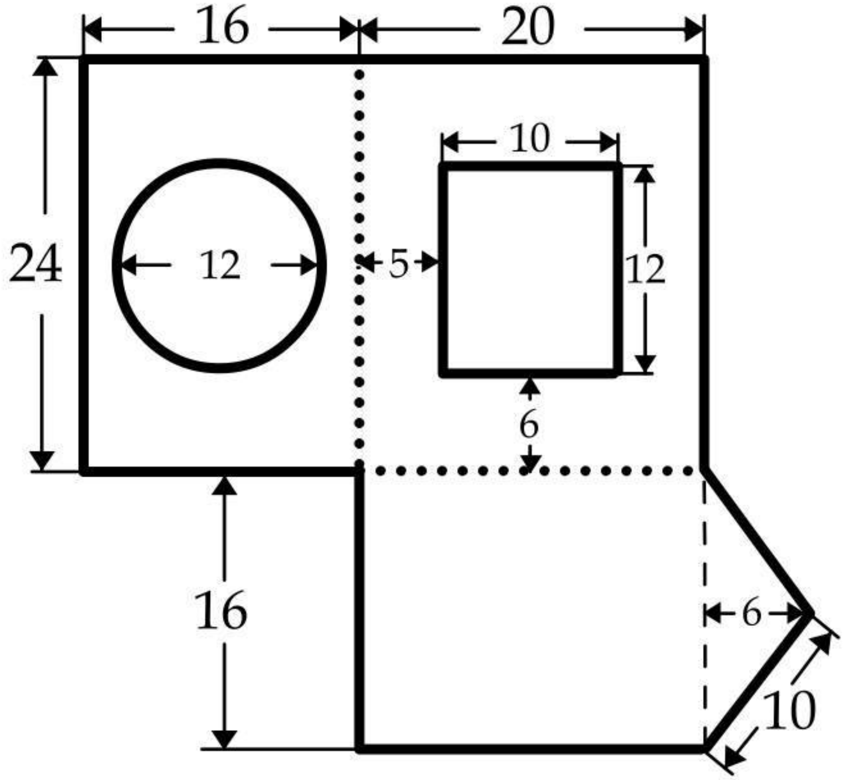
CUT OUT THE QUARTER-CIRCLE
& GLUE IT TO CARDSTOCK



Standard house template



Unit: cm



Heat Transfer: Introduction

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.

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.

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.

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 W x 10/100 x 24 hr/day x 365 days/year x 1 kW/W = 525.6 kWh/year
525.6 kWh/year x $0.15/kWh = about $80/year

Heat Transfer

Thermal energy

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.

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.

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 is 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.

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

Heat storage

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

$$Q = c_p m \Delta T$$

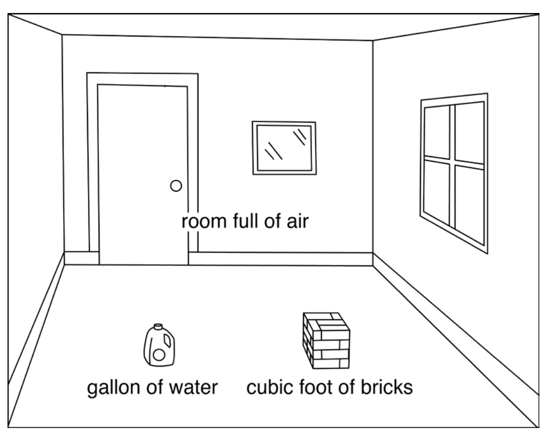
Q = heat (kJ)
c_p = specific heat (kJ/kg K)
m = mass (kg)
ΔT = change in temperature of the material (degrees Kelvin (K), or degrees Celsius (°C))

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.



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

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

= (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?

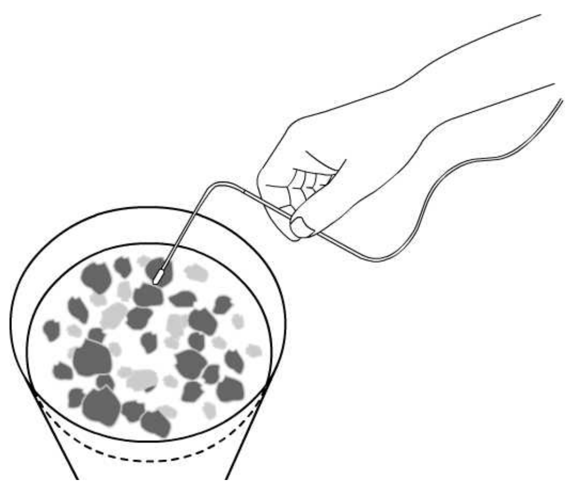
Since C_{water} is 4.18 J/g°C, what is C_{oil}? ___________

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

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.

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.

How does heat flow through solids?

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.

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:

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

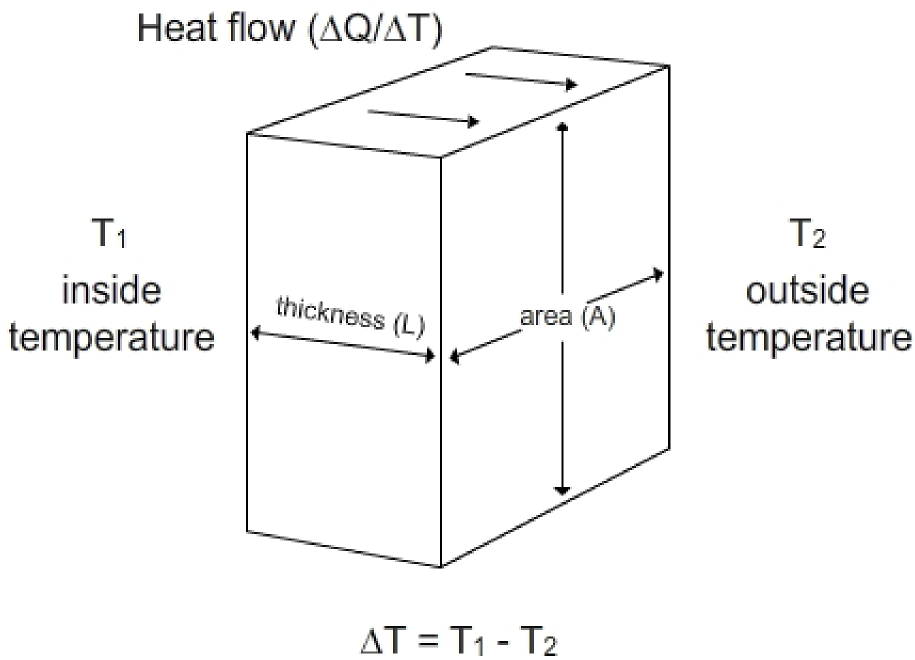
$$\Delta T = (T_2 - T_1)$$

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

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 ΔT."



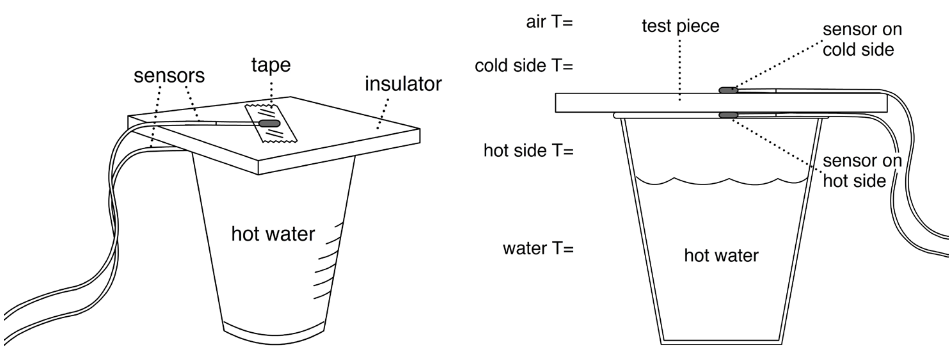
Factors that affect heat conduction through a solid material.

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.

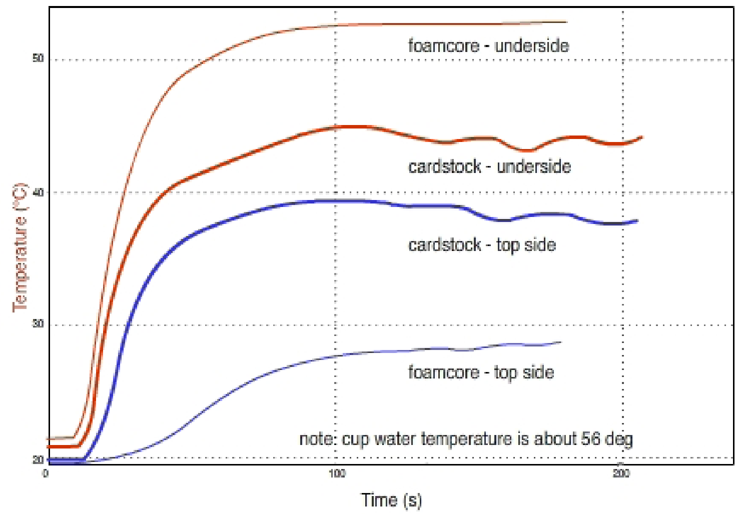
Tell students to keep the cup covered all the time to maintain water temperature. Replace with new hot water when the temperature drops.

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.

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					

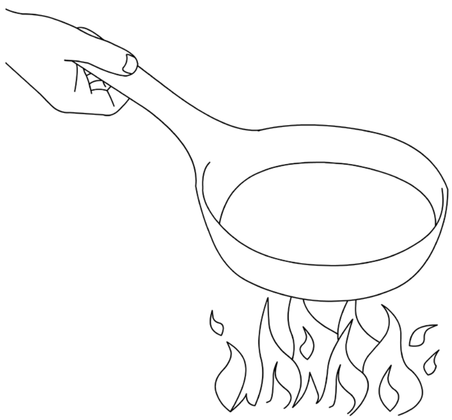
Results

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

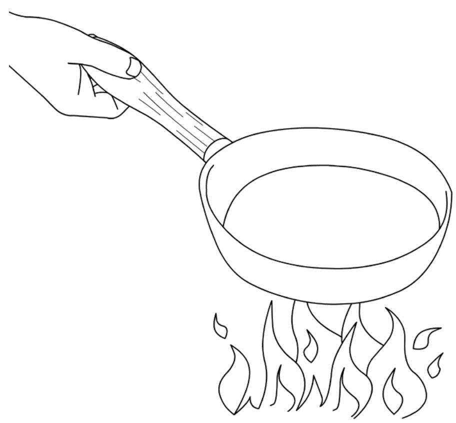
A greater temperature difference means the thermal conductivity (k) is less. The heat transfer rate is smaller, so the outer thermometer temperature is closer to the outside air temperature.

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.



A. metal handle



B. rubber handle

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

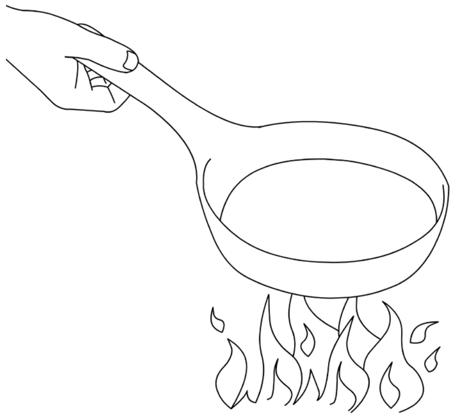
A

Which variable in the equation is being changed?

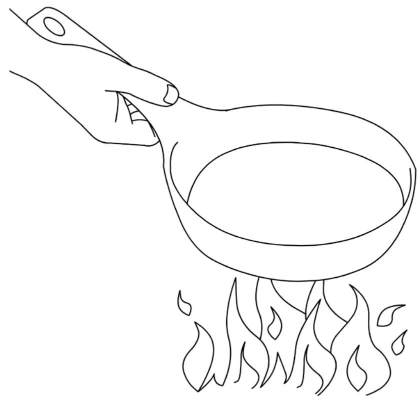
More layers or lower thermal conductivity

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



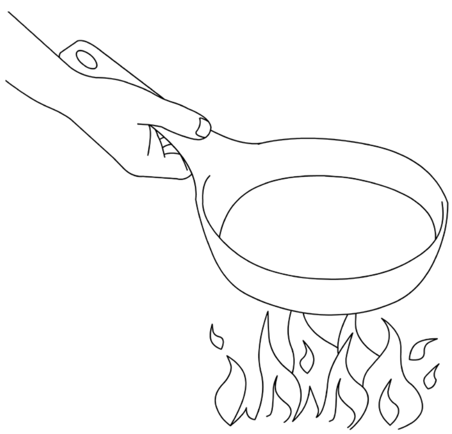
B. hand closer to the pan

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

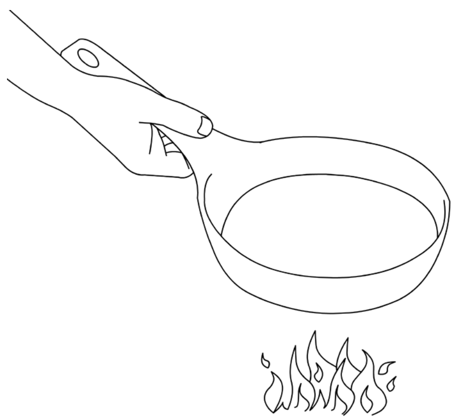
B

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 ΔT

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.

How do fluids carry heat from one place to another?

Can air carry heat into and out of a house?

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.

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

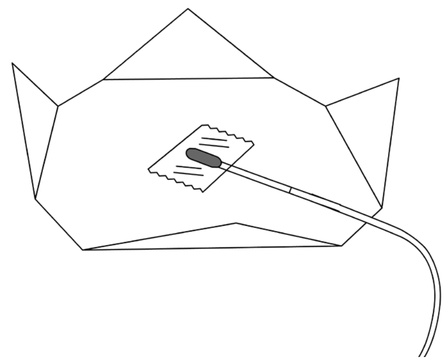
Tools & materials

- 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

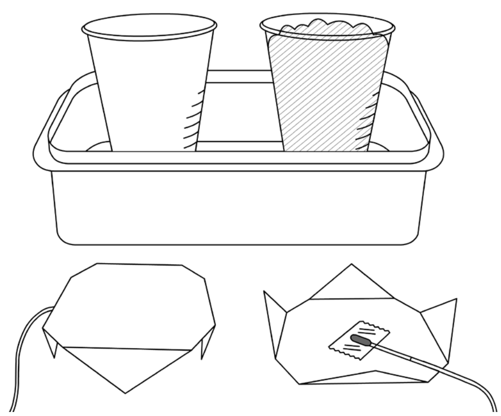
This experiment compares an insulated space to and open air space. Note that any material that inhibits air circulation – tissue paper, cloth, cellulose, packing beads – is worth a try. Although students can't see air circulation, they should be able to describe it in words or draw a diagram.

Procedure & data collection

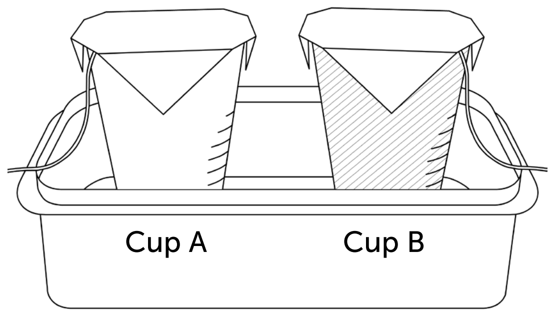
1. Cut out two pieces of cardstock slightly larger than the tops of the two cups.
2. Tape the temperature sensors to the undersides and fold over the corners to fit on the cups.



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



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.

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

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.

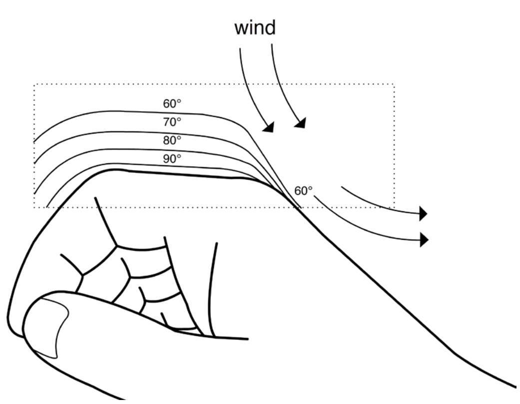
Forced convection refers to motion of a fluid that is not caused by differences in density between warm and cold ("hot air rises"). A fan (air) or a pump (water) is an example of forced convection. It is a very useful way to move heat around. For example, hot-air heating and air conditioning systems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



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.

Wind chill

Tools & materials

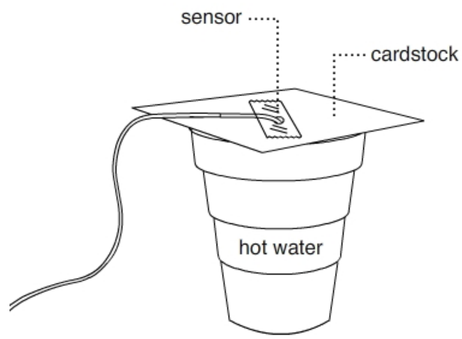
- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Metal ruler (cm)
- Scissors
- Safety utility cutter
- Fan (optional)
- Clear tape
- Styrofoam cup filled with hot water
- A piece of cardstock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

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

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.

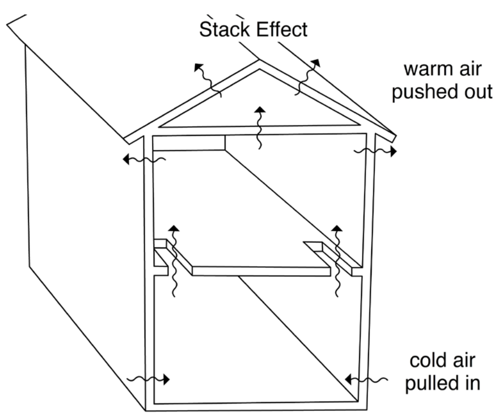
Yes, for the same reason as above. It might also increase infiltration.

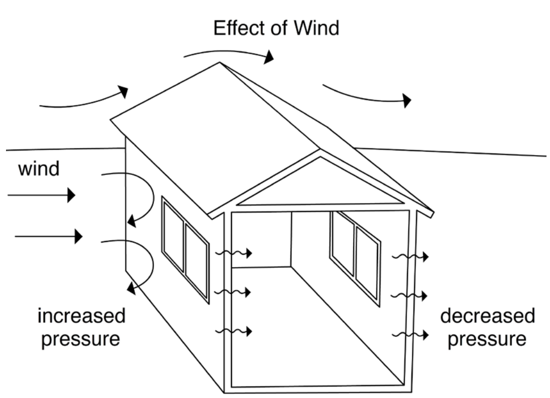
Infiltration

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.

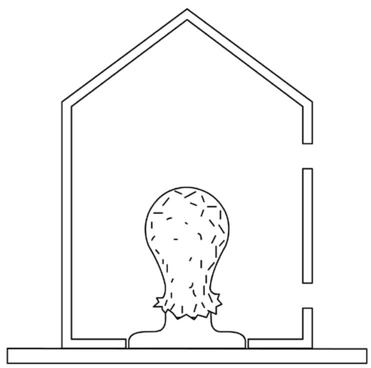
Have you noticed differences in temperature between different rooms or levels in your house, or between the ceiling and the floor? Explain why in terms of conduction and convection.

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

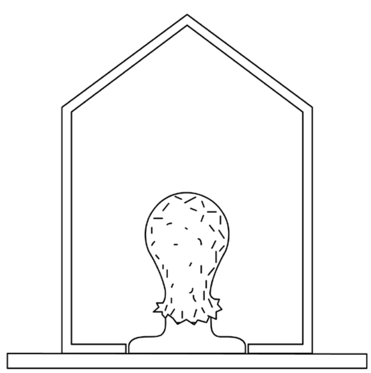
Here is a cross-section of a one-room house. There is a leaky joint near the ceiling and another one near the floor. Suppose the average temperature is 40 °C inside and 20 °C outside.

- 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.



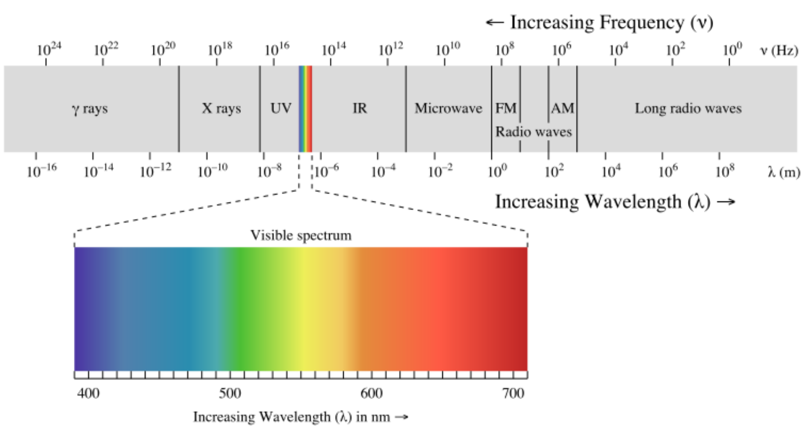
Heat Transfer

Radiation

Introduction

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.



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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.

Do objects at room temperature give off radiation?

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.

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.

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 object 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.

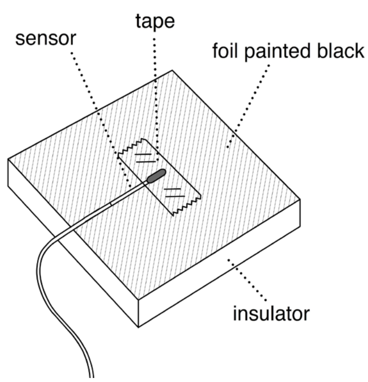
Foil is a **very** good conductor, so it doesn’t stop conduction. But because it’s shiny it does not **emit** IR radiation very much, so there is very little radiative energy loss. It also **reflects** IR, so there is very little radiative energy gain. Therefore, it adds overall insulating value **if 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

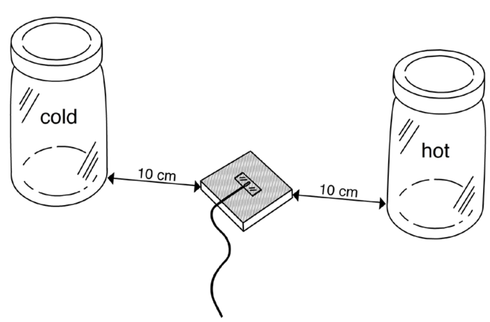
In this experiment you will use a "radiation meter"– a temperature sensor taped to a thin layer of aluminum foil that is glued to a piece of insulation and painted black. Radiation that strikes this surface will be absorbed and will quickly heat up the foil and the sensor. If the sensor temperature is 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

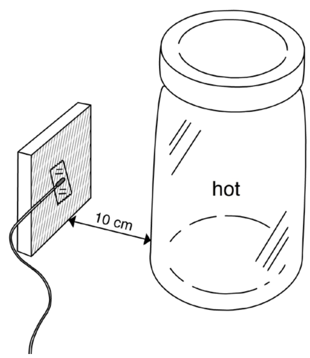
- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Hot tap water
- "Radiation meter": foil-faced rigid insulation, about 5 cm square, painted black
- Logger Lite
- USB Flash drive
- Ruler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

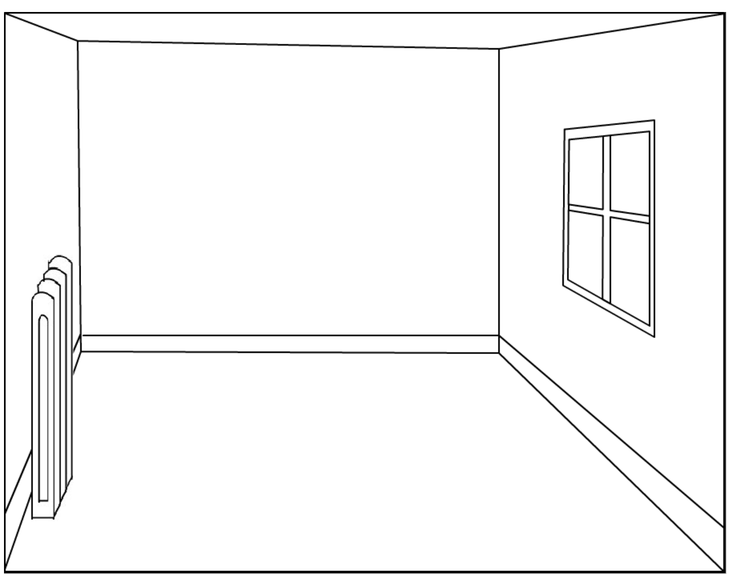
Passive solar heating consists of letting in sunlight energy (mostly visible light) and stopping heat loss, some of which is IR radiation outward from the warm building. There's a trade-off between the two processes. Larger windows gain more sunlight, but they also lose much more heat than walls. There 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.



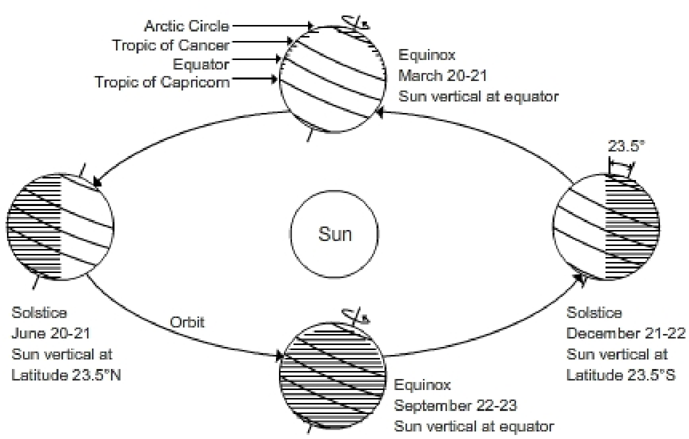
Heat Transfer
Energy from the Sun

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.

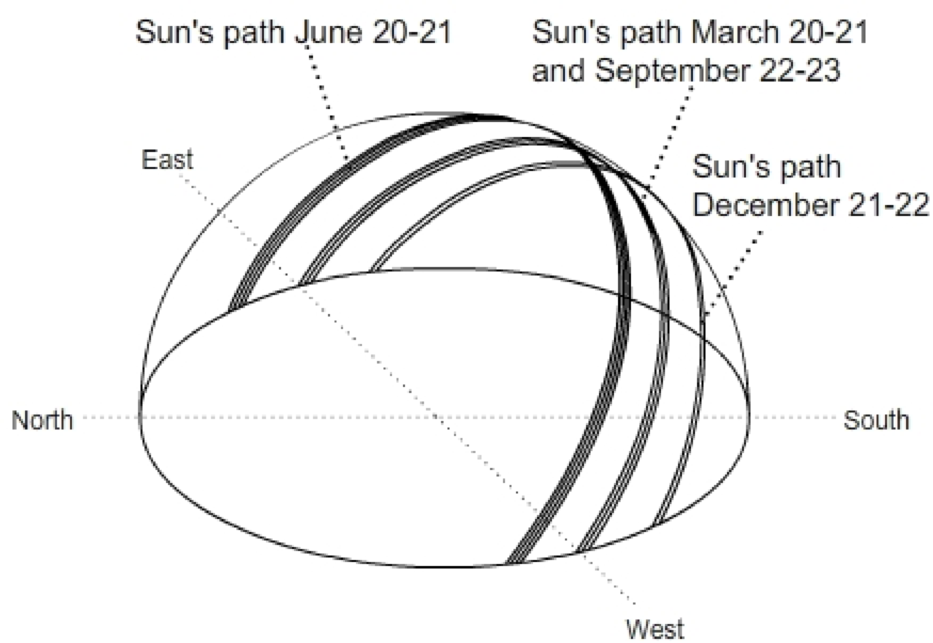
Apply this knowledge to explain how much sunlight energy can be collected using windows, roofs, and other collectors depending on their orientation.

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° 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.

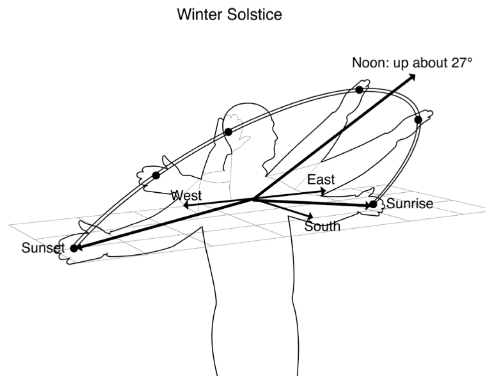
c) For the length of the day, do some Internet research. Many sites give the times of sunrise and sunset. (For 40°N, daylight is about 3 extra hours in summer and 3 fewer hours in winter.)

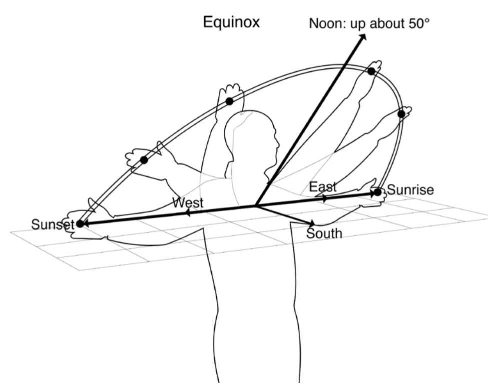
Chapter 2: Sun's path throughout the year					
Your latitude: 40°N (Boston, Massachusetts)					
Event	Date	Length of day	Height of sun at noon	Sun rises in what direction?	Sun sets in what direction?
Winter solstice	December 21-22	9 hours	26 ½° (50° - 23 ½°)	23 1/2 ° **south** of East	23 1/2 ° **south** of West
Spring equinox	March 20-21	12 hours	50° (90° - latitude)	East	West
Summer solstice	June 20-21	15 hours	73 ½° (50° + 23 ½°)	23 1/2 ° **north** of East	23 1/2 ° **north** of West
Fall equinox	September 22-23	12 hours	50° (90° - latitude)	East	West

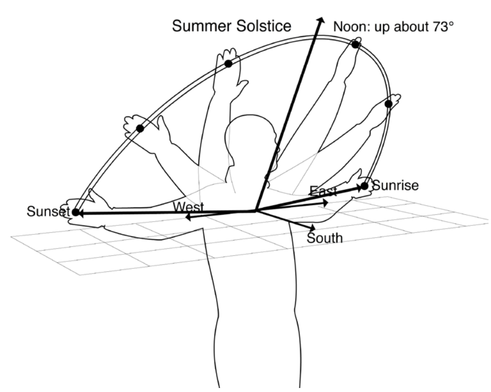
Fill out this chart together in class or assign it as homework, and then discuss the meaning of the numbers. Do the Sun's Path Calisthenics with the class (next page). This is the easiest way to show everyone exactly what the sun does all year.

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.



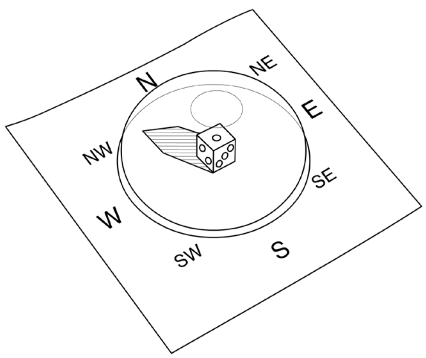




Represent the sun's path through the sky

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°. 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° 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?

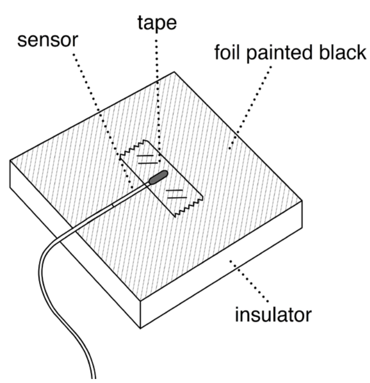
The simplest form of solar space heating is windows that face the sun. Sunlight passes through the windows and is absorbed by surfaces within the house. There are no moving parts and no mechanical systems. **This is called passive solar heating.**

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?

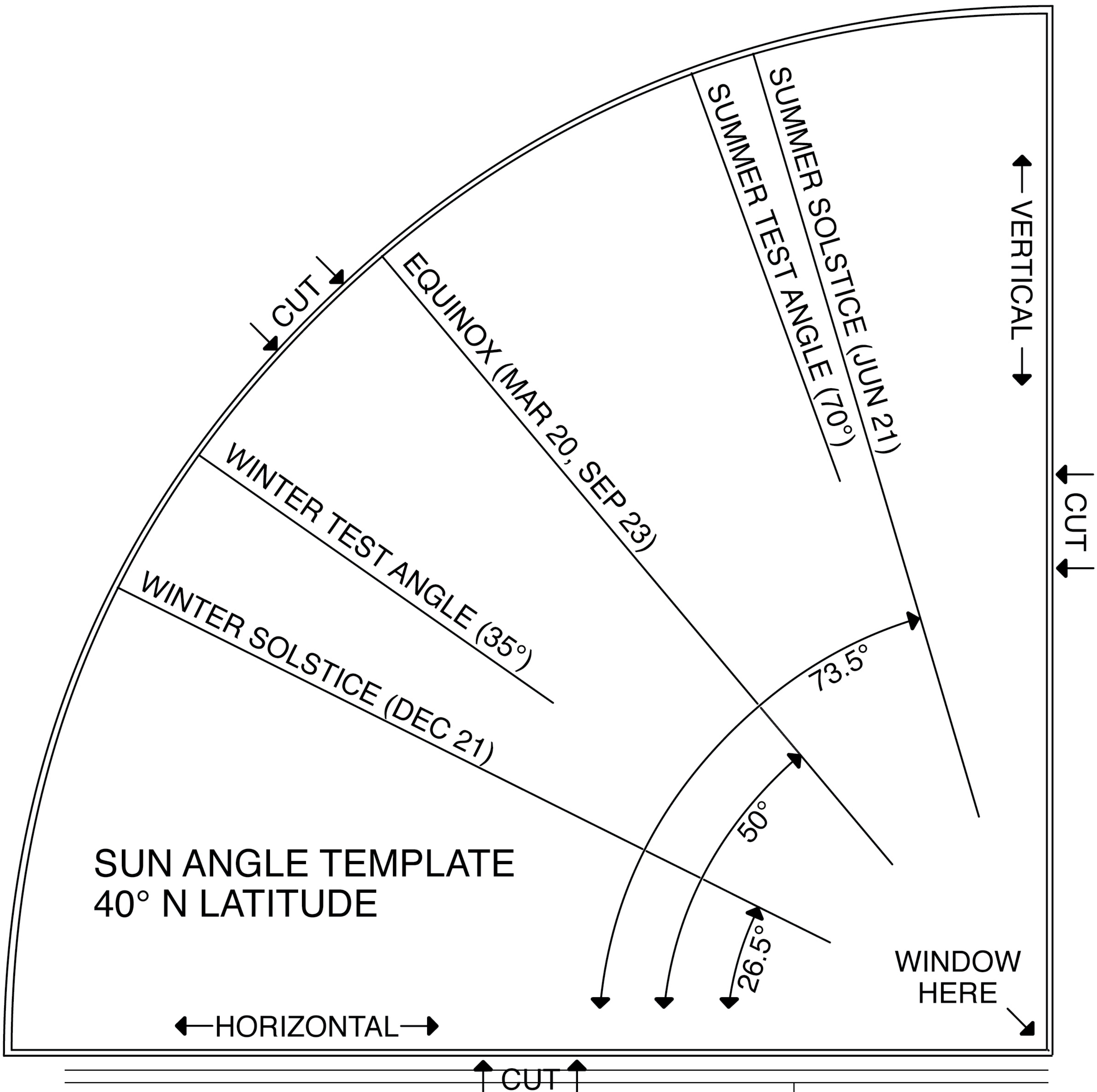
The main advantage is free energy. The main drawback is that sunlight is available only during the day, is interrupted by clouds, and is less available during the winter heating season. (That's why it's colder!) Also, passive solar heating requires large windows, which lose more heat than walls. So passive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



Design and Build a Solar House

Introduction

The goal of this engineering project is to construct and test the energy efficiency and solar heat gain of a model house. You will be working with a model rather than a full-sized house, but the principles are the same. This project uses a standard procedure for measuring the thermal performance of a house. For the house to lose heat, there must be a temperature difference. The interior must be warmer than the outside. Since you can't cool down your classroom to 0 °C, you will warm up your house to 10 °C above room temperature. This is done with a heater light bulb inside the house.

Design a model house that uses as little energy as possible to keep it warm.

As with a real house, what matters is how much of the time the furnace must be on to keep the house warm. The more it's on, the more energy is used per day and the greater your heating bill. To imitate this situation, you will record what percentage of time the heater light bulb must be on to keep the house at 10° C above room temperature.

Finally, you will perform the same test, but with a bright light shining on the house, imitating sunshine. You can then tell how much your energy bill is reduced by "solar heating."

The setting is the temperate climate of the northern United States: hot summers and cold winters, with moderate spring and fall seasons. There is a fair amount of sunshine all year, but of course the angle of the sun and the length of the day change significantly from season to season.

You have two basic strategies are to cut down on heat loss and to gain some heating from the sun during cold months. You are limited to *passive* solar strategies. Designs that depend on collectors, pumps, and fans are called *active* solar collectors and they are not available in this project.

The initial materials will be cardstock, clear acetate, and tape. You must write down a design rationale before you start building and testing. After you test it, you can start trying other materials and modifications to make it perform better. (See "Modify Solar House.")

Note: This is one chapter of a longer engineering project which includes modifying and retesting this house as well as explorations of the various mechanisms of heat transfer—conduction, convection, radiation, and heat capacity—with hands-on or model-based experiments. See: http://concord.org/engineering

Students design and build their own house, based on what they have learned about heat transfer. They are asked to come up with three distinct designs, make sketches of each, and choose the best one for construction and testing.

Learning goals:

- Explain material and design choices based on constraints or stated goals.
- Justify a design using scientific content knowledge and principles.
- Justify results using scientific content knowledge.

1. Design the house using sketches to help you picture it. Make three different designs.
2. Review the three designs and choose the best one for building and testing.
3. Make the pieces for the chosen design and assemble the house.
4. Test the house for energy efficiency.

All of the tools and materials required for this project are described in the "Tools and Materials" Appendix.

Design goals

The design of the house is up to you, but there are specific goals that you should address:

- The house has features that you think will make it energy efficient.
- The interior would be comfortable to be in on a sunny day or a cold night.
- The house should be attractive and have "curb appeal."

In addition there are geometric limitations:

- The house should fit onto a 28 x 36 cm platform.
- To make room for the heater light bulb, the walls must be at least 20 cm high and there must be room to cut a 12 cm diameter hole (the size of a CD) in the center of the floor.
- The house must be buildable – that is, not too complex and not too many pieces.
- The minimum window area is 50 cm^2.

Note: In your initial design, you are limited to cardstock and clear acetate as basic building materials.

Design rationale

Be sure students write out a serious design rationale **before** they start designing.

Before you begin designing your house on the computer, brainstorm with your team about the goals and how you will address each one. Then answer the following questions.

What shape and size of the building will contribute to the house's energy efficiency?

What roof shape will contribute to the house's energy efficiency?

How will you orient the building to take advantage of sunlight? What window sizes and placement will be good for solar gain?

Describe the other features that you would like your house to have in order to meet the design goals.

Design #1

Design procedure

Make sketches or scale drawings (whatever works best for you), so that you can picture what your house will look like and communicate your ideas to your team. If you use extra pages, tuck them into the workbook.

Ask each team member to make an independent sketch, so that each student takes responsibility for at least one design. The team as a whole can discuss and evaluate each design. Encourage them to come up with a variety of designs.

Evaluation of Design #1

Now step back and consider as a team how well Design #1 meets your goals. Here is a checklist, but add other goals if you have any.

- Energy efficiency
- Ease of building
- Attractiveness
- Shape
- Simplicity
- Size
- Comfort

Describe how Design #1 successfully met these goals.

Describe how Design #1 was not successful.

Design #2

Don’t be satisfied with your first attempt! Try an altogether different design. Again, make sketches to work out your design.

Evaluation of Design #2

Step back and consider how well Design #2 meets your goals.

- Energy efficiency
- Ease of building
- Attractiveness
- Shape
- Simplicity
- Size
- Comfort

Describe how Design #2 successfully met these goals.

Describe how Design #2 was not successful.

Design #3

Try one more altogether different design. Again, make sketches to work out your design.

Evaluation of Design #3

Step back and consider how well Design #3 meets your goals.

- Energy efficiency
- Ease of building
- Attractiveness
- Shape
- Simplicity
- Size
- Comfort

Describe how Design #3 successfully met these goals.

Describe how Design #3 was not successful.

After each team selects their preferred design, have them present it to the whole class and explain the virtues and drawbacks of their design choices.

Select your best design

You now have three designs to choose from. Each one may have features that you like or dislike. Review the design goals and select one of them for building and testing. To help you choose, fill out the rating chart below. 3=excellent, 2=good, 1=fair, 0=bad

Results			
Goal	House #1	House #2	House #3
Energy efficiency			
Ease of building			
Attractiveness			
Shape			
Simplicity			
Size			
Comfort			

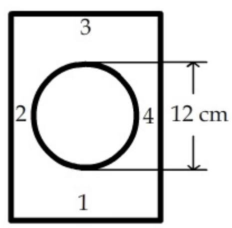
Which design will you select?

Explain why you selected the design that you did.

Construction

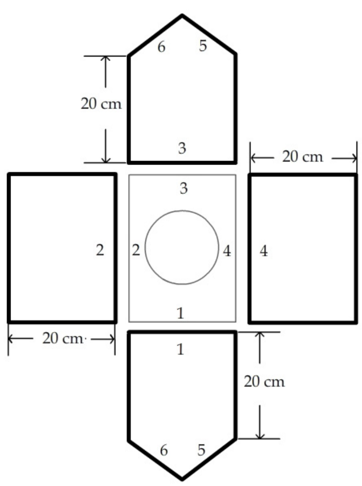
1. You have designed a building with a certain shape and features. Now you need to make all of the pieces and assemble it. The example below shows how you could proceed.

2. Draw the outline (first floor plan) of your house on cardstock. To accommodate the heater light bulb, it must be large enough to place a circle on it with a diameter of 12 cm. It must fit entirely on the base.



3. Cut a circle out of the center of the floor that is 12 cm in diameter (the size of a CD) so that the light bulb heater can fit in.

4. Make walls for your house that are 20 cm high and go all the way around the floor plan. Note that if you want a gable roof (see example below), some of the walls will have triangular tops. Use the layout shown below to find the wall lengths from the floor plan. Draw out the walls on cardstock, all next to each other to save materials. Cut out the walls.

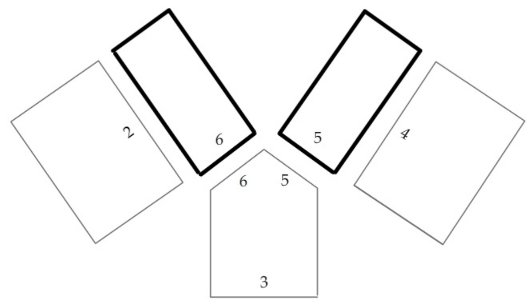


Tools & materials

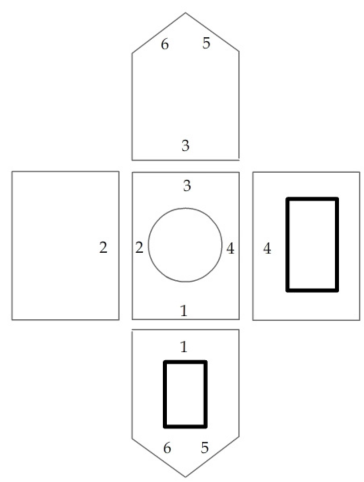
- Scissors
- Pencils
- Metal ruler (cm)
- Protractor
- Safety utility cutter
- Cardstock (approximately one 20x30 in sheet)
- Acetate sheets (8.5 x 11 in) for windows
- Masking tape and/or clear tape
- 28 x 36 cm platform

Here is one procedure for making a house from a sketch. The design shown is the same as the standard house used in Chapter 1. Students can use another procedure if they wish. Encourage them to group the pieces to cut down on measuring and reduce paper waste.

5. Decide what kind of roof will work. Try to use a design that is not too hard to build. Draw all of the roof pieces on cardstock. You can use the wall lengths to determine roof dimensions, as shown in the drawing below. If you are uncertain about some dimensions and angles, make them oversized and trim them down to fit.



6. Draw and cut out windows that are in the walls (and roof, if any) and tape pieces of acetate over them on the inside.



7. Tape the edges of your house together. Here is one set of steps that you could follow: It works well to follow these steps:

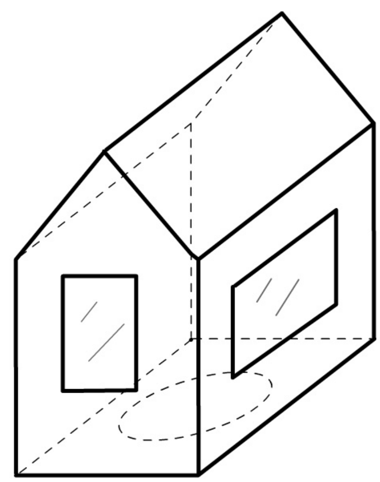
   a) tape the wall pieces together

   b) tape the roof pieces together

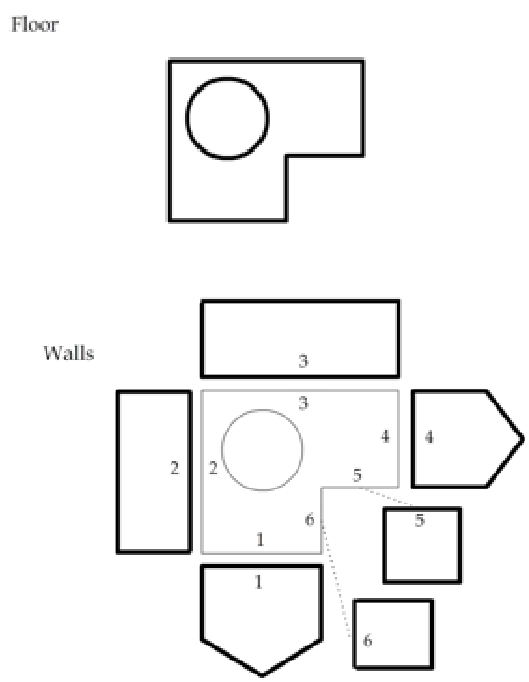
   c) tape the roof to walls

   d) tape the floor to walls

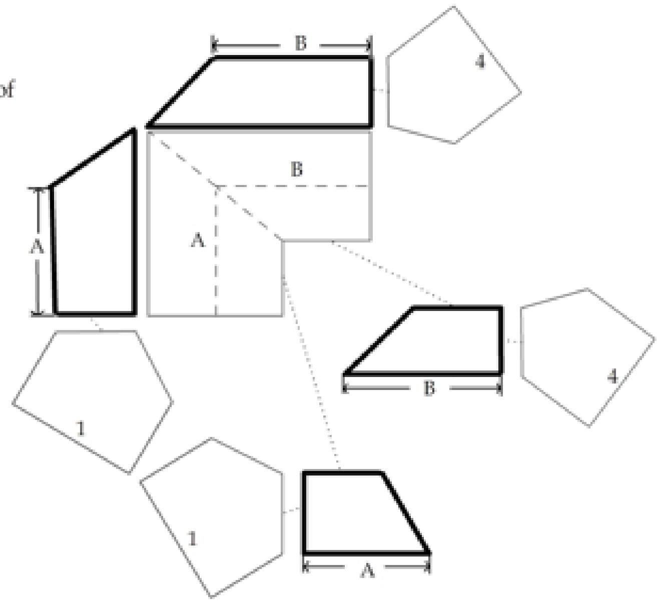
Here is the assembled house.



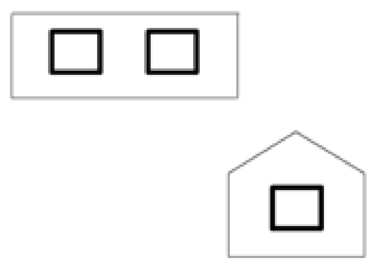
Here is another more complex example – an L-shaped house. Note that the dashed lines on the floor plan (A and B) give the lengths of the roof pieces at the ridge.



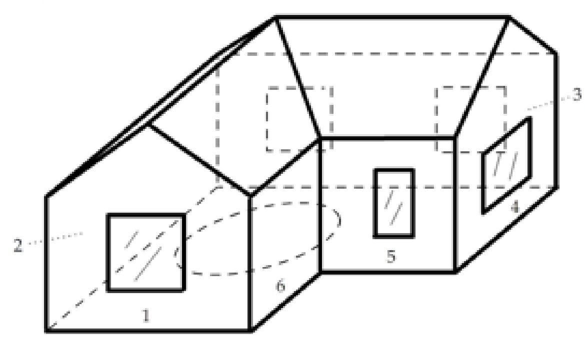
Roof



Windows



Assemble



8. Make a hole in one wall for the temperature sensor 10 cm above the floor. Pick the wall that is farthest from the heater light bulb. The sensor will go 3 cm into the house and it must be at least 5 cm from the heater light bulb.

9. Calculate the total floor area and window area of your house. Also calculate the window area that faces south. Your measurements can be rounded to the nearest centimeter. Fill out the table below.

	Your house
Floor area (cm^2)	
Window area (cm^2)	
Window/floor ratio	
South-facing window area (cm^2)	
South window/floor ratio	

House heating test

Your goal in testing your house is to measure how much power it takes to keep your house 10 °C warmer than the air around it.

Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- One 40 W light bulb heater in a socket with an inline switch, covered with foil (page 23)

NOTE: If your house is large or has lots of window area, you may need to change the 40 W heater bulb to 75 W. Be sure to use 75 W instead of 40 W when you calculate the average power requirement on the next page.

This is the basic house heating test. Point out that the students are acting as a "human thermostat." Review how it is analogous to a real house furnace, which turns on and off to keep the house at a constant temperature. The furnace output (power) multiplied by the percentage of time it is on (percent) is the average power requirement to keep the house warm.

Collect data

1. Connect one temperature sensor to your computer. Set up data collection for one reading per second and a total time of 600 seconds.
2. Measure the room temperature. We will assume it stays reasonably constant throughout the experiment. Record temperature in the table below.
3. Calculate your target temperature: 10 °C above room temperature. Record your room and target temperature in the table below.
4. Insert the temperature sensor in the hole you made in the house. It must be pushed through the wall, so that it is 3 cm from the wall.
5. Turn the heater on.
6. Start collecting data when the sensor is a few degrees below the target temperature.
7. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A).
8. When the sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table below (B).
9. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
10. Stop collecting data.
11. Click the "scale" icon to fit the graph to your data.
12. Save the data file.
13. Calculate the average power requirement to keep the house warm by filling out the rest of the table below.

House heating test	
Room temperature: _____°C	
Target temperature: _____°C	
Upper limit (target temperature + 0.2): _____°C	
Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * the proportion of time the heater is on)	_______W

Once the room temperature has been measured, the whole class can use the same value throughout the project unless a large change (more than 2-3 °C) is noticed. Then students don't need to wait for their house to cool down between experiments. This will save considerable time.

Note: the house does not need to cool down between this and the next experiment (page 18) so students can save time by doing them both together.

Make a table of everyone's results so that they can be compared and discussed. Include the floor and window areas, which may help explain some of the differences.

Results

What specific features of your design contributed to or detracted from the energy performance of the house?

Based on your results what design changes would you propose to improve the performance of these design features?

Solar heating test

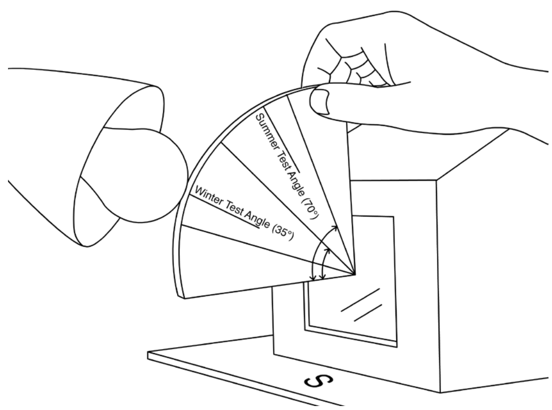
Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- One 40 W light bulb heater
- One 300 W sun light bulb in a gooseneck desk lamp (page 23)
- Template for measuring "sun's" angle (page 25)

Insist that students be very careful with the light bulbs, turning them off when not in use.

Collect data

1. Connect the temperature sensor to your computer.
2. Set up data collection for one reading per second and a total time of 600 seconds.
3. Assume that room temperature has not changed. Calculate the target temperature (room temperature + 10 °C) and enter it in the table below.
4. Set up the gooseneck lamp with a 300 W bulb in it, due south of the building. The tip of the bulb should be 20 cm from the house window and aimed downward at about a 35° angle, as if it were noon in winter at 40° North Latitude. Use the template to position the sun.



5. Switch the heater light bulb and the sun light bulb on.

   NOTE: The bulb is very hot. Be careful not to touch it, and wait until it cools down to move or store it. Turn it off except while doing the experiment.

6. Start collecting data when the sensor is a few degrees below the target temperature.
7. When the upper sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A). Leave the sun on.
8. When the upper sensor reaches 0.2 °C below the target temperature, turn the heater ON. Record the time in the table below (B).
9. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
10. Stop collecting data.
11. Click the “scale” icon to fit the graph to your data.
12. Save the data file.
13. Calculate the average power requirement to keep the house warm by filling out the rest of the table.

Add these results to the shared table for discussion.

Solar heating test	
Room temperature: _____°C Target temperature: _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. Proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * proportion of time heater is on)	_______W
H. Power requirement without sun	_______W
I. Solar contribution	_______W

Results

How did this solar-heated house perform compared to the house without sunlight?

What specific features of your design contributed to or detracted from its performance as a passive solar house? Include the evidence from your tests that support your claims.

Based on your results what design changes would you make to improve its performance?

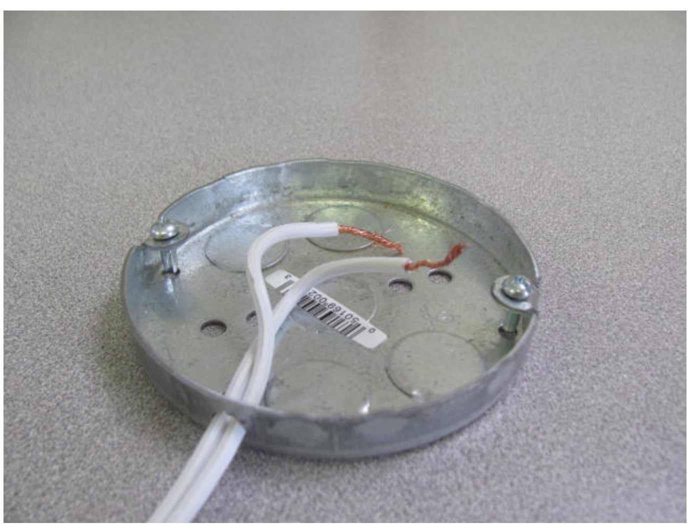
What are the advantages and disadvantages of having large south-facing windows?

Advantages: more solar gain in winter, less in summer. Cold surface in winter.
Disadvantages: large conductive loss in winter, conductive gain in summer.

Fabricating a light bulb heater

Procedure

1. Cut off the outlet end of the extension cord. Strip the wires.
2. Install the inline switch in the extension cord. Note that the common (ground) wire has ribs and the live (hot) wire is smooth. Make sure the switch interrupts the hot wire.
3. Drill a 5/16″ (8 mm) hole through the side of the pancake box and insert the cord.

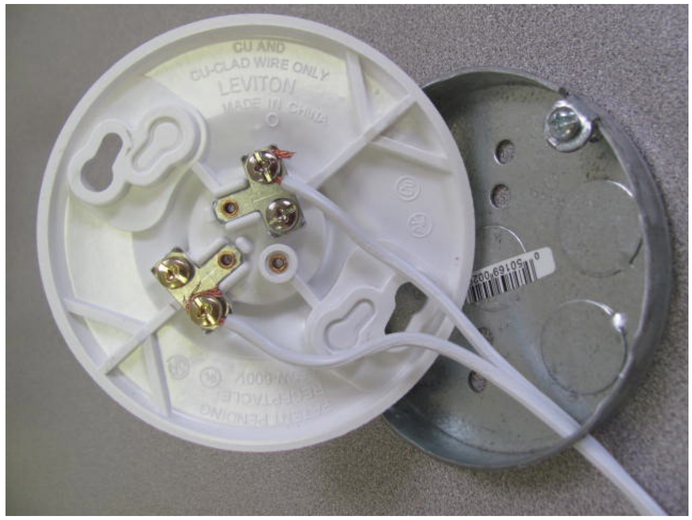


Tools & materials

The required parts, available at any hardware store, are:

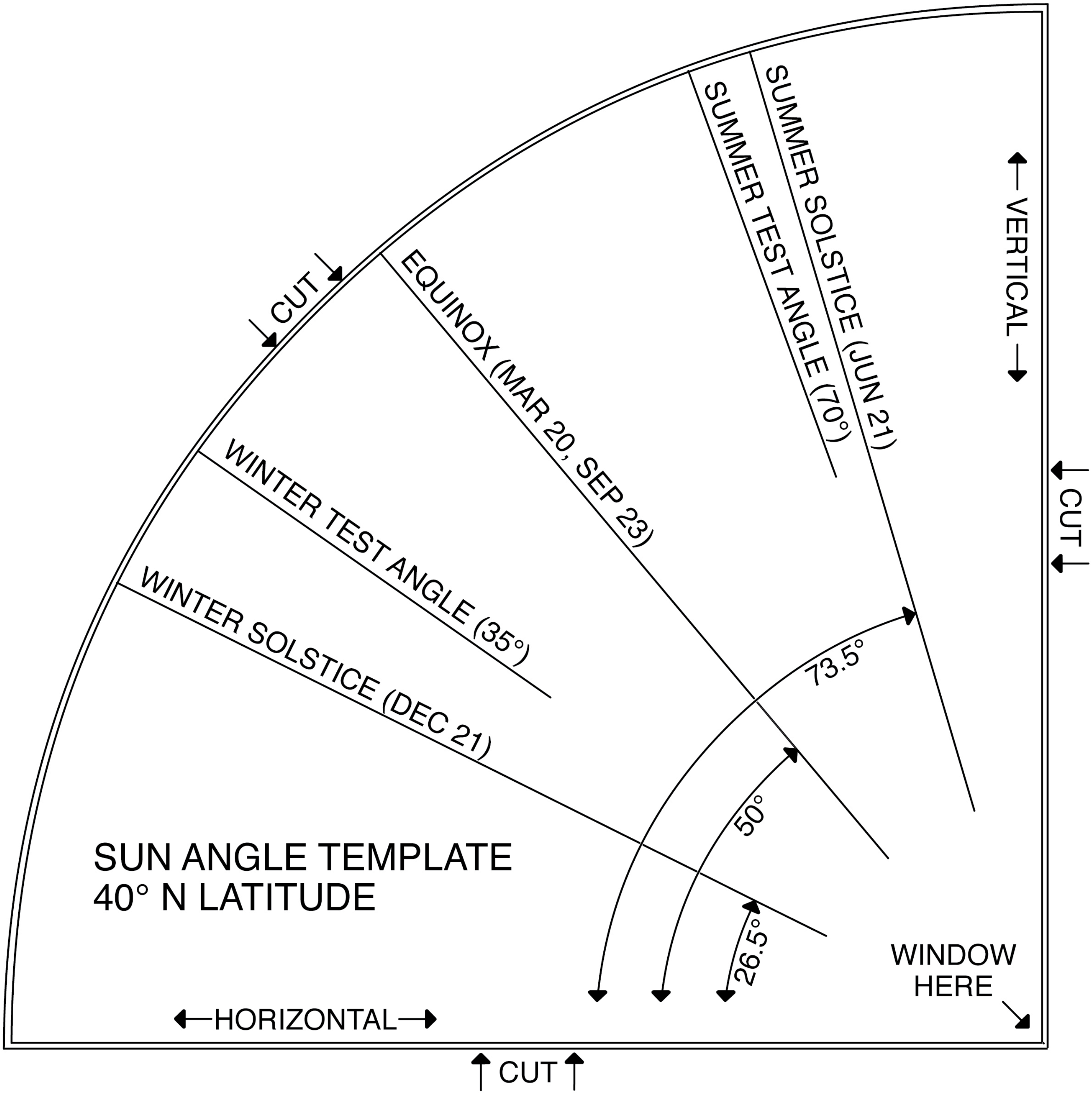
- keyless socket (plastic or ceramic)
- 6' extension cord
- inline switch
- metal pancake box
- 40 W light bulb
- aluminum foil

4. Attach the wires to the keyless socket. The ribbed (ground) wire is attached to a silver screw and the smooth (hot) wire is attached to a brass-colored screw.



5. Screw the socket to the pancake box. Cover the bulb with a layer of foil to cut down on radiation.

CUT OUT THE QUARTER-CIRCLE
& GLUE IT TO CARDSTOCK



Modify Your Solar House

Introduction

Before you begin this chapter, you must have completed "Design and build a solar house."

Now that you have tested your own energy-efficient house design, it's time to modify it and make it work better. A cycle of design, testing, redesign and retesting is an essential part of engineering.

Your success will be measured using the same tests as before:

- keeping the house warm with a heater light bulb (the "no sun" condition)
- reducing the heating requirement using sunshine from a low angle (the "winter sunshine" condition)

You can add other materials from what's available, and also change the design — whatever you think would improve the performance of the house. You can also add "additions" on the outside if you think they will help — solar greenhouses, for example.

Every change *must have a design rationale*, including your theory for why it will help, based on the scientific ideas from the Heat Transfer chapter.

To make your engineering process more systematic, you will be asked to tackle one improvement at a time and measure the effect of that improvement. You will also be asked to do some specific investigations before making your design changes.

Note: If you have your own ideas and prefer to skip over the suggested improvements, make your modifications and then go to page 17 to test your results.

How much can you improve the energy performance of your house?

In this chapter, students explore modifications to reduce their house energy use – adding a ceiling, insulating the walls, and adding a sunspace. If there is time, the changes should be made and tested one at a time. If this is not practical, skip to page 17. Encourage students to apply their scientific knowledge and reasoning to this engineering task.

Make a table of everyone's results so that they can be compared and discussed. Include the floor and window areas, which may help explain some of the differences.

Note: This is one chapter of a longer engineering project which includes modifying and retesting this house as well as explorations of the various mechanisms of heat transfer—conduction, convection, radiation, and heat capacity—with hands-on or model-based experiments. See: http://concord.org/engineering

Explore natural convection

Often the most valuable first step in making a house energy efficient is to stop air from leaking in and out. Cold air entering and hot air escaping is a large source of heat loss, in both older and newer construction.

You will conduct a series of experiments to explore convection (the motion of air) in your house and then see how much you can improve its performance.

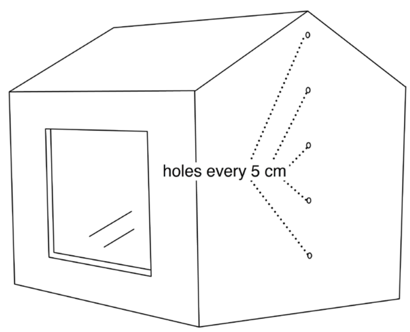
Tools & materials

- Two fast-response temperature sensors (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- Small square of cardboard (5x5 cm)
- Tape
- One 40 W light bulb heater
- Metal ruler
- Your house

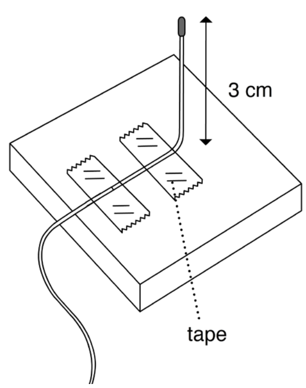
This experiment requires two students working in close c ollaboration. Emphasize that one sensor is a monitor to keep the house 10 °C above room temperature, and the other is movable. Make sure students understand the sample graph before they begin. The top hole can be through the roof if that works better with their design.

Procedure & data collection

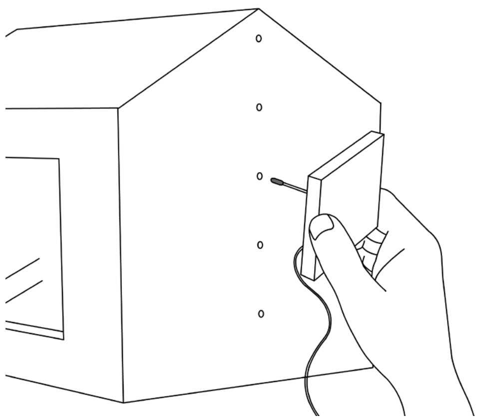
1. Tape one sensor into the hole in your house house at 10 cm. This will be your **fixed monitoring temperature sensor**.
2. Make a series of holes in the end wall opposite the monitoring sensor every 5 cm above the bottom of the house. Use a sharp pen or pencil. The holes should be just large enough so that the movable temperature sensor can be inserted into the house. (The top hole can be through the roof, if your house has a hipped roof.)



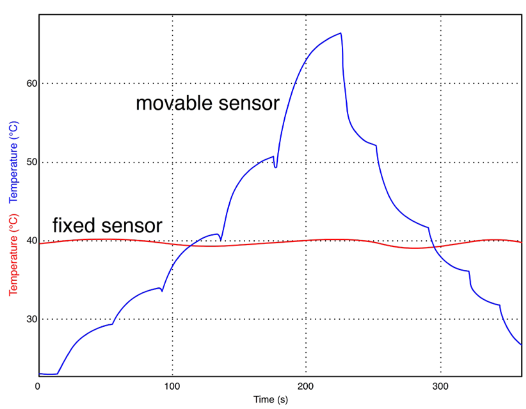
3. Tape the other sensor to a small piece of cardboard (about 5x5 cm) with a bend in the wire so that the end sticks up about 3 cm. This will be your **movable temperature sensor**.



4. Start collecting data. Record the initial temperature in the table below.
5. Turn the heater on. Let the temperature of the fixed sensor rise until the inside is 10 °C above the initial temperature.
6. Have one team member take responsibility for keeping the reading of the fixed sensor within 0.2 °C or less of the target temperature. Turn the heater off and on to maintain a constant temperature for the fixed sensor.
7. Have another team member measure the temperature at each height by inserting the movable sensor into each hole in turn, from 5 cm to 25 cm, and then back down again.



8. You must wait in each position long enough for the temperature to approach a settled value – about 30 seconds. It's OK not to wait for the exact settled value. The graph will look something like this:



9. Record the temperature values at the different heights in the table below.

10. Calculate the average temperature for each height.

Temperature at different heights			
Initial temperature: _____°C Target inside temperature: _____°C (Initial + 10 °C)			
Height (cm)	Temperature (going up)	Temperature (going down)	Average of two temperatures
5			
10			
15			
20			
25			

Results

What is the maximum temperature difference from bottom to top?

What is the difference between the fixed monitoring sensor and the highest temperature?

Analysis

If the fixed sensor shows a constant temperature, explain what creates the observed temperature pattern seen in the graph of the moveable sensor.

Hot air is less dense than cold air, so it rises from the light. The hotter air therefore is measured close to the roof and cooler air measured close to the floor.

House heating test with a ceiling added

Tools & materials

- One temperature sensor
- Computer
- Cardstock for ceiling
- Small square of foamcore or cardboard (5 x 5 cm)
- Tape
- One 40 W light bulb heater
- Scissors
- Your house

Now test the improvement in overall performance when you add a ceiling. Use the same tests as before to measure how much power it takes to keep your house 10 °C warmer than the air around it.

Construction

1. Trace the floor of the house on a piece of cardstock.
2. Cut this piece out to make a ceiling for the house.
3. Bend the piece a bit so that it can be pushed through the hole in the bottom of the house. Push it up to make a “ceiling” at the tops of the walls, which should be 20 cm high. It should stay roughly in place without tape, but you can add a few small pieces of tape if necessary.

Collect data

1. Connect the temperature sensor to your computer. Use one temperature sensor.
2. Measure the room temperature. Record it in the table below.
3. Calculate your target temperature, 10 °C above room temperature, and record it in the table.
4. Install the sensor in the standard monitoring position, through a hole in the wall 10 cm up and 3 cm into the house.
5. Turn the heater on.
6. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A).
7. When the sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table below (B).
8. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
9. Stop collecting data.
10. Click the “scale” icon to fit the graph to your data.

11. Save the data file.

12. Calculate the average power requirement to keep the house warm by filling out the rest of the table below.

House heating test with ceiling	
Room temperature: _____°C Target temperature (room temperature + 10): _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * proportion of time heater is on)	________W

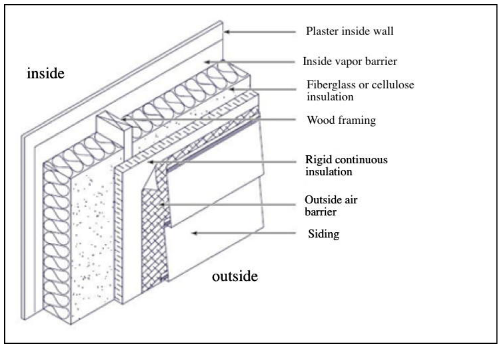
Compare your current house performance with previous experiments.

Summary of results	
Condition	Power requirement
Standard house	
Your model house rom “Build Your Own Solar House” section	
Ceiling added	

Conductivity of the walls

Energy efficient houses are always very well insulated. Often some parts of the building envelope are insulated more than other parts.

Here's a typical well-insulated wall. Each layer has a purpose. The vapor barrier stops moisture from migrating outward. The insulation slows heat flow. The continuous insulation blocks air circulation and thermal bridging through the wood, which is less insulating that the insulation around it. The outside air barrier stops infiltration.



Air spaces inside walls may or may not provide some insulating value. If they are wider than about 2 cm, convection loops form and heat is easily transferred across them. If they are narrower than that, convective loops do not form and they provide insulating value.

Reduce heat loss with insulation

Decide how you will insulate the walls of your house. You may draw from the following materials:

- 1 sheet card stock
- 1 sheet foamcore
- 2 sheets acetate

Here are the rules:

Only use materials that are equally available to all of the teams, unless your teacher decides otherwise.

When possible, apply insulation to the outside of the existing house, so that the interior volume remains about the same.

Do not place any material closer than 5 cm from the heater light bulb.

After you have insulated your house, test its performance.

You may provide other insulating materials, such as more foamcore or aluminum foil, if you wish. The point is for students to try a variety of strategies with limited resources and explain their reasons for doing so.

Collect data

1. Connect the temperature sensor to your computer. Use one temperature sensor.
2. Measure the room temperature. Record it in the table below.
3. Calculate your target temperature, 10 °C above room temperature, and record it in the table below.
4. Install the sensor in the standard monitoring position, through a hole in the wall 10 cm up and 3 cm into the house.
5. Turn the heater on.
6. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table (A).
7. When the sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table (B).
8. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table (C).
9. Stop collecting data.

Note that a test without the sun is followed immediately by the same test with the sun. The house does not need to cool down in between tests.

10. Click the "scale" icon to fit the graph to your data. Enter the data in the "without sun" column below.
11. Save the data file.
12. Set up the sun light bulb at the winter test angle, turn it on, repeat this experiment. Enter the data in the "with sun" column below. Save the data file.
13. Calculate the average power requirement to keep the house warm, with and without the sun, by filling out both columns in the table below.

House heating test with insulation	
Room temperature: _____°C Target temperature (room temperature + 10): _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * proportion of time heater is on)	_______W

Summary of results	
Condition	Power requirement
Standard house	
Your model house rom "Build Your Own Solar House" section	
Insulation added	

Sunspace addition

Sunspace, sunrooms, or greenhouses can be used to collect sunshine for heating. They are also pleasant spaces in the winter, although they have drawbacks as well. Build a sunspace addition to your house. Explore the temperatures in it and how it affects your house heating requirement.

What are the temperatures in a sunspace?

Can a sunspace contribute heating energy to a house?

Tools & materials

- One temperature sensor
- Computer
- Acetate
- Cardstock
- Tape
- One 40 W heater light bulb
- One 300 W sun light bulb in a gooseneck desk lamp
- Scissors
- Sun angle template (page 20)
- Your house

Construction

Build a sunspace addition, following these guidelines:

- You can use acetate, cardstock, and tape.
- The house should form one wall of the sunspace. That is, the sunspace should be against the house.
- The sunspace can be on any side of the house, but remember that your goal is for it to gain solar heating in the winter.
- The sunspace floor area should be **one-half the area of the house or smaller.**

The sunspace is meant to be a more open design challenge. Students should feel free to try a variety of arrangements, materials, and shapes for a sunspace – against the south wall, as an addition to the east or west, square or sloping, all acetate or partly insulated.

Since the sunspace will probably heat up more than the house, the challenge is to get the heat from the sunspace into the house while the sun shines. It may prove to be quite difficult. Students should try various strategies and justify them.

Collect data

1. Place one sensor in the house at the standard monitoring position, 10 cm up and 3 cm in.
2. Slip the other sensor into the sunspace about 10 cm up and near the wall of the house.
3. Tape a piece of paper on the outside of the sunspace so that it casts a shadow on the sunspace sensor. This will make sure the sensor measures the air temperature and is not heated directly by radiation.
4. Record the room temperature in the table below.
5. Calculate your target temperature, 10 °C above room temperature, and record it in the table below.
6. Turn on both the heater light bulb and the sun light bulb. Start collecting data.
7. When the monitor sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A).
8. When the monitor sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table below (B).
9. When the monitor sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
10. Stop collecting data.
11. Click the “scale” icon to fit the graph to your data.
12. Save the data file.
13. Calculate the average power requirement to keep the house warm by filling out the rest of the table below.
14. Start collecting data. Turn on both the heater light bulb and the sun light bulb. Heat up the house to about 10 °C above room temperature. This will be your house target temperature.

15. Keep the house within 0.2 °C of the target temperature by turning **both** the heating bulb and the sun bulb on and off. Observe at least two on-off cycles.

16. Scale the data with the “scale” button.

17. Save your data.

House heating test with sunspace #1	
Room temperature: _____°C Target temperature (room temperature + 10): _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * proportion of time heater is on)	_______W
H. Previous requirement without sun	_______W
I. Sunspace contribution (G-H)	_______W

Results

Compare the graphs of the two sensors – inside the house and inside the sunspace. How are they the same and different?

Analysis

How could you explain the differences?

Improve the solar heating contribution from the sunspace

See if you can improve the construction of the sunspace.

Your design must accomplish two things:

- The sun light bulb must heat up the sunspace.
- The heat must be transported into the house.

Repeat the test each time as as you refine the sunspace. Note that two tables have been provided. Describe your experimental conditions in each case. Try at least two improvements and take data for each. For example:

- Connect the sunspace to the house with cutout openings, so the heat can flow from the sunspace to the house.
- Add black paper inside the sunspace to increase solar absorption.

After you have made improvements, test your house again, using the table on the next page. Also fill out the “Summary of results.”

House heating test with sunspace #2	
Room temperature: _____°C	
Target temperature (room temperature + 10): _____°C	
Upper limit (target temperature + 0.2): _____°C	
Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * proportion of time heater is on)	_______W

Summary of results	
Description of experiment	Power requirement
Before sunspace is added – no sun	
Sunspace added	
Improvement:	

Procedure for standard house heating test

If you skipped over the suggested improvements and did your own, use the steps below to measure the results. Your goal in testing your house is to measure how much power it takes to keep your house 10 °C warmer than the air around it. This is the same test you used with the standard house.

Collect data

1. Connect one temperature sensor to your computer. Set up data collection for one reading per second and a total time of 600 seconds.
2. Measure the room temperature. We will assume it stays reasonably constant throughout the experiment. Record temperature in the table below.
3. Calculate your target temperature: 10 °C above room temperature. Record your room and target temperature in the table below.
4. Insert the temperature sensor in the hole you made in the house. It must be pushed through the wall, so that it is 3 cm from the wall.
5. Turn the heater on.
6. Start collecting data when the sensor is a few degrees below the target temperature.
7. When the sensor reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (A).
8. When the sensor drops to 0.2 °C below the target temperature, switch the heater ON and record the time in the table below (B).
9. When the sensor again reaches 0.2 °C above the target temperature, switch the heater OFF and record the time in the table below (C).
10. Stop collecting data.
11. Click the "scale" icon to fit the graph to your data.
12. Save the data file.
13. Calculate the average power requirement to keep the house warm by filling out the rest of the table below.

Tools & materials

- One fast-response temperature sensor (for example, the Vernier surface temperature sensor STS-BTA)
- Computer or other graphing interface for temperature sensor
- One 40 W light bulb heater in a socket with an inline switch, covered with foil (page 23)

NOTE: If your house is large or has lots of window area, you may need to change the 40 W heater bulb to 75 W. Be sure to use 75 W instead of 40 W when you calculate the average power requirement on the next page.

House heating test	
Room temperature: _____°C Target temperature: _____°C Upper limit (target temperature + 0.2): _____°C Lower limit (target temperature – 0.2): _____°C	
Event	Time (from data table)
A. Turn heater OFF at upper limit	
B. Turn heater ON at lower limit	
C. Turn heater OFF at upper limit	
D. Total cycle time (C - A)	
E. Total time ON (C - B)	
F. proportion of time the heater is on (C - B) / (C - A)	
G. Average power requirement (40 watts * the proportion of time the heater is on)	_______W
H. Power requirement before improvements	_______W

Connection to buildings: Lessons learned

Application

What lessons or guidelines did you learn from these experiments that would apply to real buildings?

a) adding a ceiling

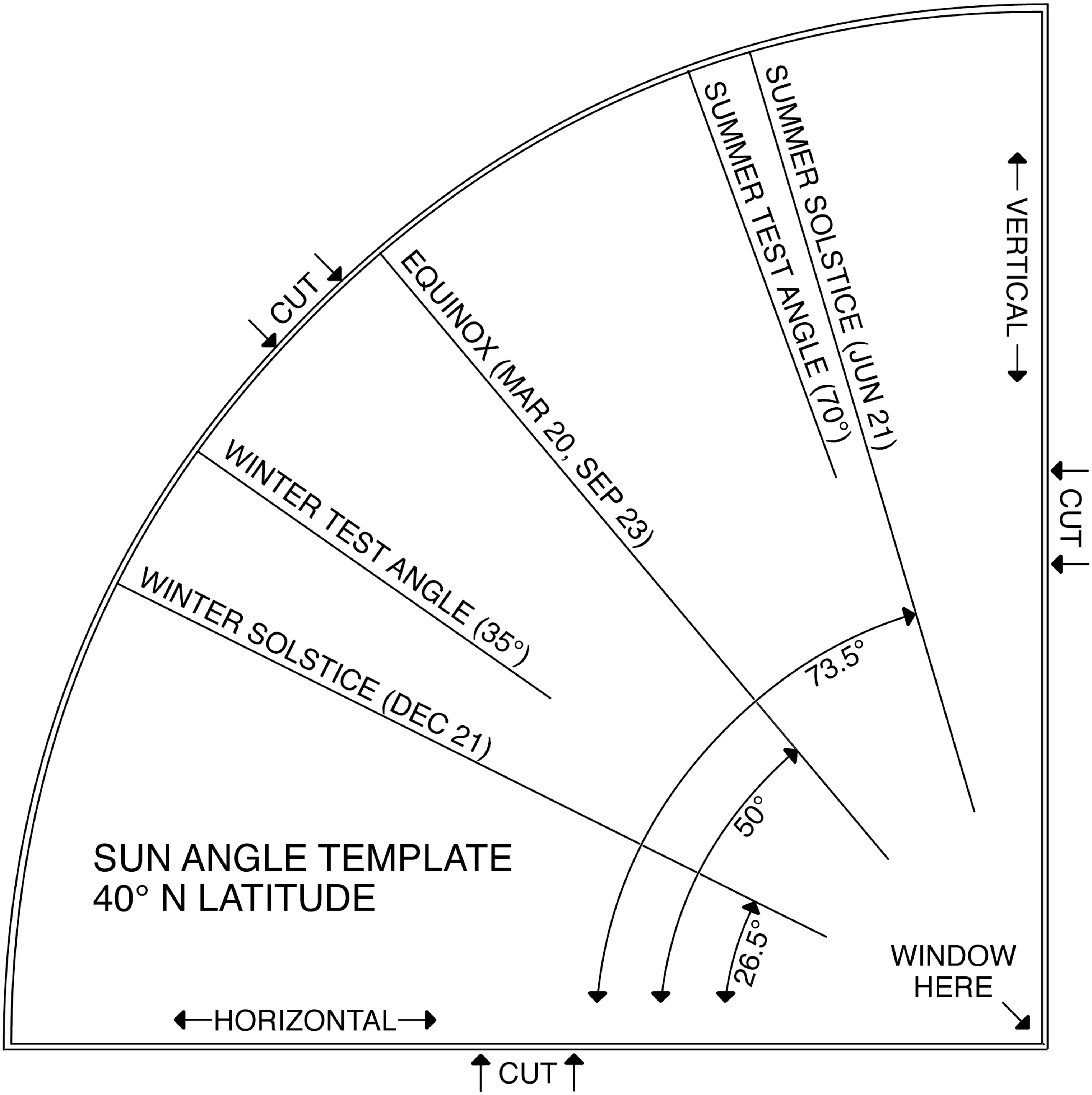
b) insulating the walls

c) adding a sunspace

This open-ended question has many possible answers, such as:

- Hot air rises to the top and settles there, so ceilings and less tall rooms are easier to heat.
- Insulation makes a very large difference in heating energy requirements, so insulate as well as possible.
- Sunspaces can contribute solar gain, but only if there is an effective way to move the sunspace heat into the house and close off the sunspace at night.
- Window and sunspace orientation toward the south is important.
- Heat-absorbing surfaces (black paper) help in a sunspace.
- Foil acts as an insulator by reflecting IR back into the room.

CUT OUT THE QUARTER-CIRCLE
& GLUE IT TO CARDSTOCK



Solar House Project Summary

This provides a format for a summary of the entire project. Use it as guidelines for a written report or a class presentation.

Introduction

Imagine that a new energy-efficient housing development is looking for a project engineer. The project engineer will be responsible for all design and construction decisions related to heating and cooling energy use. The project involves a variety of house designs that all need to be energy efficient.

This final report will be used to persuade a review committee that you have the understanding and inventiveness to apply what you have learned to the entire housing project.

Your project was a preliminary study to identify the most important features of an energy-efficient house. The committee will be looking at the energy performance of your model house as one indication of your skill. It will also look at the design ideas and materials you used to accomplish this. Equally important, however, you must demonstrate that you understand the science behind the energy-efficient designs and would be able to make further improvements and develop other designs.

Complete all of the sections below.

Here is the outline of your report:

- House performance: experimental data
- Explanation of house performance and design choices
- Heat flow analysis
- Conclusion

Note: This is one chapter of a longer engineering project which includes modifying and retesting this house as well as explorations of the various mechanisms of heat transfer—conduction, convection, radiation, and heat capacity—with hands-on or model-based experiments. See: http://concord.org/engineering

Energy-Efficient House Project: Final Report

Name:

House dimensions

Floor area (cm^2):

Total window area (cm^2):

The surface area calculation can be omitted.

Total surface area (cm^2):

HOUSE PERFORMANCE: EXPERIMENTAL DATA

Gather the results of your experimental data in the table below.

Summary of experimental data		
Winter heating	Power requirement (W)	Percentage of power requirement compared to the standard house*
Standard house, no sun condition		= 100%
Standard house, winter sun condition		
Own house, no sun condition		
Own house, winter sun condition		
Own house, with all modifications, no sun condition		
Own house, with all modifications, winter sun condition		

* For example, if the standard house requires 20 W and "own house, no sun condition" requires 15 W, the percentage is 15/20 = 75%.

EXPLANATION OF HOUSE PERFORMANCE AND DESIGN CHOICES

House design

Describe the major features of your design (for example, the shape of the house, placement of windows, material choices). In each case, describe the feature, how it functions, and your evidence that it works that way. Use scientific explanations from the Heat Transfer unit to explain how each of these features affects energy efficiency. Refer to your experimental data to support your claims.

Modifications

What did you learn from your experiments that guided your design choices? Explain what features were added after initial experiments, what features were modified, and how they affected the energy performance of the house. Include evidence from your experiments.

HEAT FLOW ANALYSIS

Draw a picture of your house in vertical cross section, which is a slice through the center in the North-South direction. Label the wall, window, and roof materials. Label North and South.

Describe where and how heat is lost from your house and how different modifications changed the rate of heat loss. Use evidence from the Heat Transfer Basic units to describe the process.

On your drawing show your best guess for the temperature distribution throughout the house. Write down what you think are likely values of temperatures in various locations, assuming the outside temperature is 5 °C, the heater temperature is 40 °C, and the average temperature in the house is about 25 °C.

Draw arrows to show how you think heat flows around inside your house as well as in and out of your house.

CONCLUSION

Given what you know now, if you were starting again from scratch and could make a completely different design, what materials and design features would you choose for your house? Why?