# Heat Transfer: Introduction

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

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

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

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

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

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

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

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

# Heat transfer and thermal equilibrium

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

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

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

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

# Power and energy

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

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

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

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

# Heat Transfer

## *Thermal energy*

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Note the video tutorial.

# Heat storage

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

$$Q = c_p m \Delta T$$

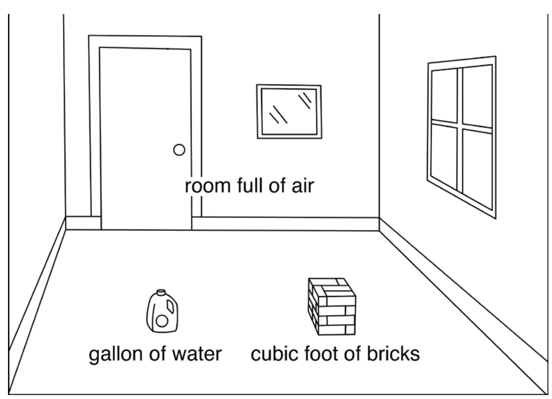
**Q = heat (kJ)**
**$c_p$ = specific heat (kJ/kg K)**
**m = mass (kg)**
**ΔT = change in temperature of the material (degrees Kelvin - K, or degrees Celsius - °C)**

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

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

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

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



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

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

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

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

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

The following set of models allows you to use this principle to explore the factors that affect heat storage.

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## 1A: Measuring heat storage

The first model you can try has two identical rectangular objects that are in contact. They have different initial temperatures that can be adjusted. Open Model 1A and follow the instructions, then answer the following questions.

When you run the model, what happens?

Why do the two thermometers reach the same temperature?

Record the results of at least three different setups of initial temperature differences.

| Results from Model 1A | | |
|---|---|---|
| Initial temperature of left object | Initial temperature of right object | Final temperature |
| | | |
| | | |
| | | |
| | | |

In Model 1A, what rule can be used to determine the final temperature of the two objects if the objects are identical?

Why does a warm object feel warm when you touch it?

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## 1B: Heat storage depends on specific heat

Substances vary greatly in their ability to store thermal energy. The specific heat is a property of a substance that tells how much the temperature goes up when a given amount of energy is added. A large specific heat means you have to put a lot of energy into it each each degree increase in temperature.

In this model the specific heat $c_p$ of each object is different, as shown by the labels in the boxes. Note that the mass of the two objects in the model is the same. The temperature difference is fixed. But the specific heats can be adjusted. Open Model 1B and follow the instructions, then answer the following questions.

Predict the final temperature under each circumstance using the equation:

$$(c_p m \Delta T)_{\text{left}} = -(c_p m \Delta T)_{\text{right}}$$

Write your predicted results and the measured results of your three experiments below.

**Results from Model 1B**

| Left-hand $c_p$ | Left-hand initial temperature | Right-hand $c_p$ | Right-hand initial temperature | Final temperature |
|---|---|---|---|---|
| 1000 | 40 | 2000 | 10 | |
| | | | | |
| | | | | |

Make a general claim. For two materials with different heat capacities, how will the equilibrium temperature be affected?

## 1C: Heat storage depends on size

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In this model the specific heat of each rectangular object is different, as shown in the label below them. The size of an object is a stand-in for mass in the equation, that is, how much material there is. According to the rule of conservation of energy, the amount of heat flowing in or out from the left rectangle must be equal to the amount of heat flowing out or in from the right rectangle.

$$(c_p A \Delta T)_{\text{left}} = -(c_p A \Delta T)_{\text{right}}$$

where $A_{left}$ is the size (area) of the left object and $A_{right}$ is the size (area) of the right object

Open Model 1C and follow the instructions, then answer the following questions.

Record the results of your experiments below. Note that these should all be results where the final temperature is close to 25 °C (within 1 °C).

| Results from Model 1C | | | |
|---|---|---|---|
| Left-hand $c_p$ | Left-hand area | Right-hand $c_p$ | Right-hand area |
| 1000 | | 2000 | |
| 1000 | | 500 | |

Use the following equation to explain your results.

$$(c_p A \Delta T)_{\text{left}} = -(c_p A \Delta T)_{\text{right}}$$

Why does it take longer to heat up a bigger house?

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## 2A: Regulating temperature

This model compares the rate of temperature rise when the heat capacities of the boxes are different but the power inputs are the same. This is an exaggerated version of a masonry house (large heat capacity) compared to a wood-frame house (small heat capacity). Open Model 2A and follow the instructions, then answer the following questions.

Which box heated up more quickly? Why?

After you turn the heater on and off, describe the graphs. Which curve was steadier and which was more variable? What was the range of temperature variation in each?

In the model, the power input is the same for both boxes. Why does the temperature change more for one than the other?

## Connection to buildings: Heat storage capacity

Application

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

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

# Heat Transfer

## Conduction

### *Introduction*

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

How does heat flow through solids?

### Factors that affect heat conduction

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

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

$(\Delta Q/\Delta t)$ **= the rate of heat conduction (kJ/s)**
$\Delta T$ **= temperature difference across the material**
$L$ **= thickness of the layer (m)**
$A$ **= area of the material ($m^2$)**
$k$ **= thermal conductivity of the material per unit thickness (kJ/m/s/°C)**

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

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

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

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

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

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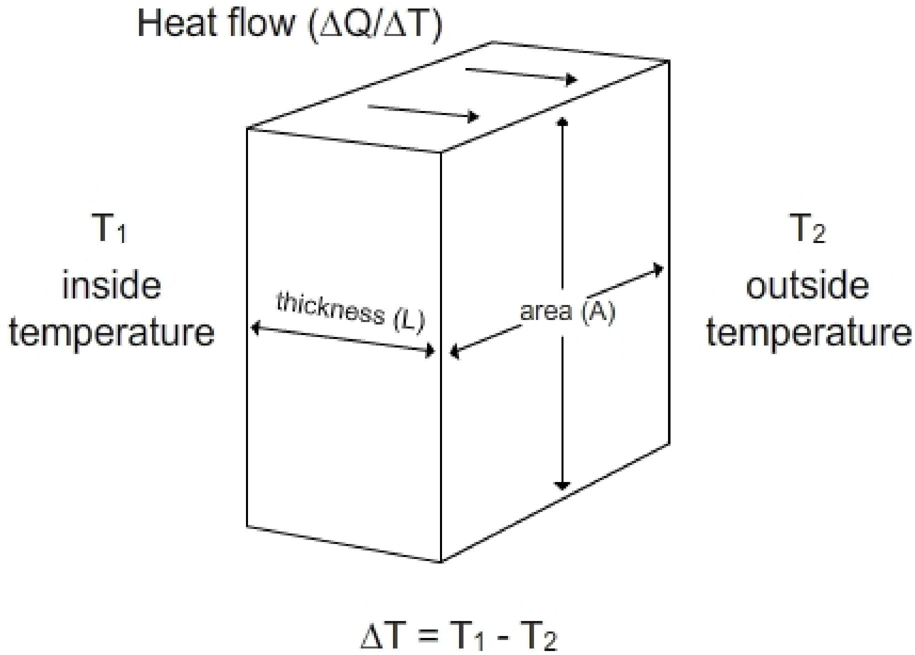


*Factors that affect heat conduction through a solid material.*

## 3A: Heat conduction through materials

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Here is a model comparing four common building materials – metal (steel or aluminum), stone (or other masonry, such as concrete or brick), fiberglass, and wood. Open Model 3A and follow the instructions, then answer the following questions.

List the four materials in order of rate of heat transfer.

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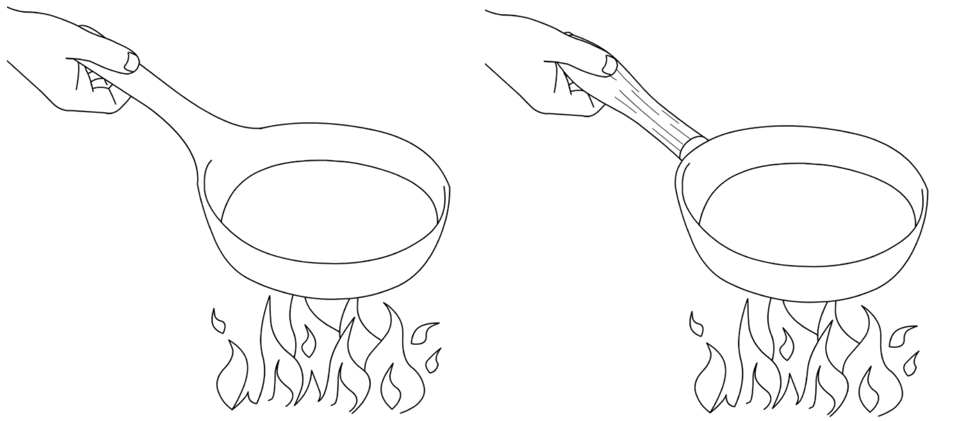
## 3B: The effect of thermal conductivity



A. metal handle B. rubber handle

When you cook with a frying pan, you may notice that a rubber handle stays cooler than a metal handle.

In this model you will explore the role of thermal conductivity (k) on heat flow. Open Model 3B and follow the instructions, then answer the following questions.

Which material has a greater conductivity, the upper or lower material? What is your evidence from the model?

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

## 3C: The effect of wall thickness

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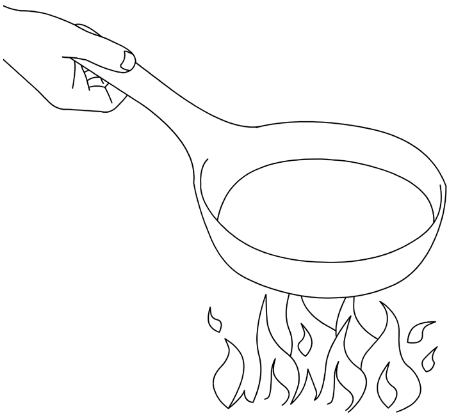
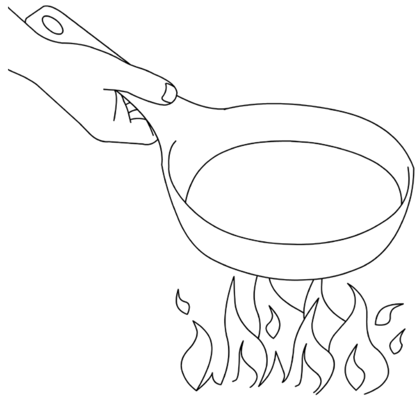


A. hand farther up the handle



B. hand closer to the pan

You may notice that your hand feels hotter if you hold the handle of a frying pan in the middle as opposed to the end.

In this model you can explore the effect of thickness L on heat flow. This is a two-dimensional model, so the thickness is represented by the distance between the heat sources – a left-to-right measurement. Open Model 3C and follow the instructions, then answer the following question.

Compare the two cases. How does wall thickness affect heat flow?

Look back at the equation on page 1. How does wall area (A) affect heat flow?

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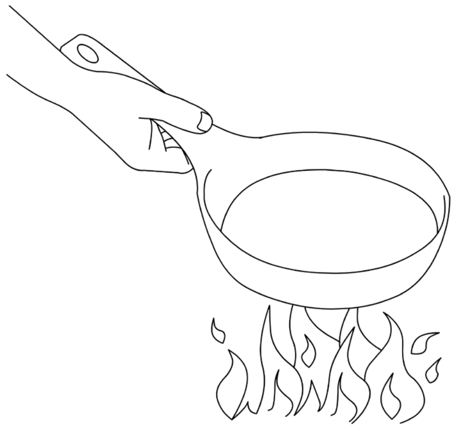
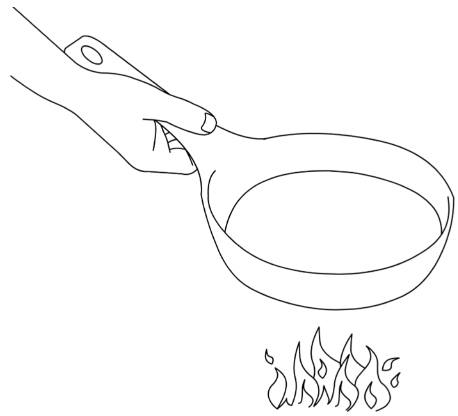
## 3D: The effect of temperature difference



A. more intense heat source



B. less intense heat source

If the fire below a frying pan is more intense, your hand will feel hotter.

In this model you can explore how the amount of heat conducted through an object depends on the temperature of the heater. Open Model 3D and follow the instructions, then answer the following questions. Note that the right-hand thermometer starts at 0 °C.

| Results from Model 3D | |
|---|---|
| Temperature of heater | Temperature of thermometer at half hour (model time) |
| 50 | |
| | |
| | |

Does a hotter object lose heat more quickly than a colder object?

## Connection to buildings

### Background

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

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

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

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

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

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

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

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

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

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

# Connection to buildings

## Application

Describe the advantages of a well-insulated house.

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

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

# Heat Transfer

## Convection

How do fluids carry heat from one place to another?

Can air carry heat into and out of a house?

### *Introduction*

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

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

### *Natural convection*

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

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## 4A: Natural convection

What would it be like if there were no natural convection, that is, if air didn't move around when heated or cooled? This model compares the two situations: convection by air that is free to move and conduction through a solid with the same conductivity as air. Each is placed above a hot plate. Open Model 4A and follow the instructions, then answer the following questions.

Measure top temperatures at half an hour for different bottom temperatures. Record the results of your experiments below.

| Results from Model 4A | | |
|---|---|---|
| Bottom temperature | Top temperature above air | Top temperature above solid |
| | | |
| | | |
| | | |

Based on the model, explain the difference between convection and conduction. Which is faster?

## 4B: Slow down convection

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Suppose you could interrupt convection flow with one or more barriers. This is essentially what insulation does. Most insulation consists of tiny pockets of air separated by thin walls or fibers that stop large-scale convection. Open Model 4B and follow the instructions, then answer the following questions.

How can convection in air be reduced?

Give two examples of natural convection in a house that you have personally observed.

Try other arrangements the slow down convection. Fill in the following chart.

| Condition | Temperature |
| --- | --- |
| no barrier | |
| barrier | |
| other (describe) | |
| | |
| | |

## Forced convection

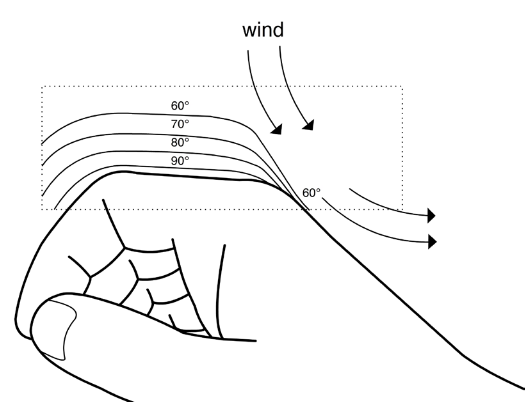
Forced convection refers to motion of a fluid that is not caused by differences in density between warm and cold ("hot air rises"). A fan (air) or a pump (water) is an example of forced convection. It is a very useful way to move heat around. For example, hot-air heating and air conditioning systems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

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

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

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

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



## 4C: Forced convection

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Here's a model that explores forced convection, the effect of wind blowing across a hot surface. Open Model 4C and follow the instructions, then answer the following questions.

Record the temperatures of the upper and lower sensors after running the model for 0.4 model hours as shown on the graph (not real time) under three wind conditions. The model will stop automatically.

| Results from Model 4C | | |
|---|---|---|
| Wind speed | Temperature at upper sensor | Temperature at lower sensor |
| Low | | |
| Medium | | |
| High | | |

Explain why the two circles have different temperatures.

Think of other examples of the wind chill effect and how it is minimized.

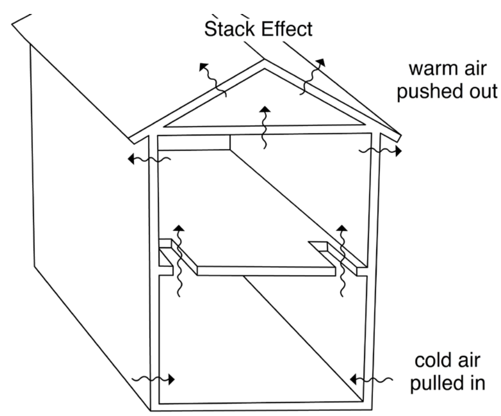
# Infiltration

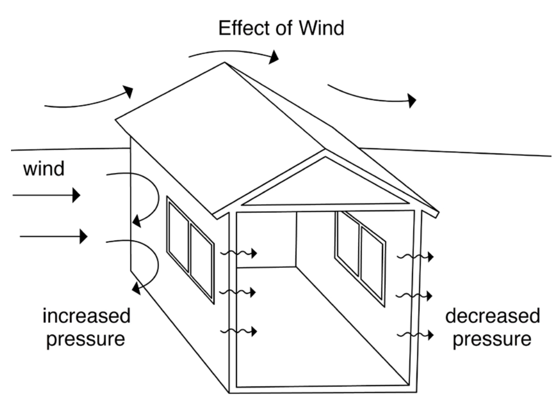
## *Introduction*

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."



## 4D: Stack effect

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Here is a model that demonstrates the stack effect. Open Model 4D and follow the instructions, then answer the following questions.

Draw the convection pattern as shown in your model after you changed the size and location of leaks in each room. Describe or use arrows to show the motion of the air.

What causes more loss of energy, a leak near the ceiling, or a leak near the floor? Why?

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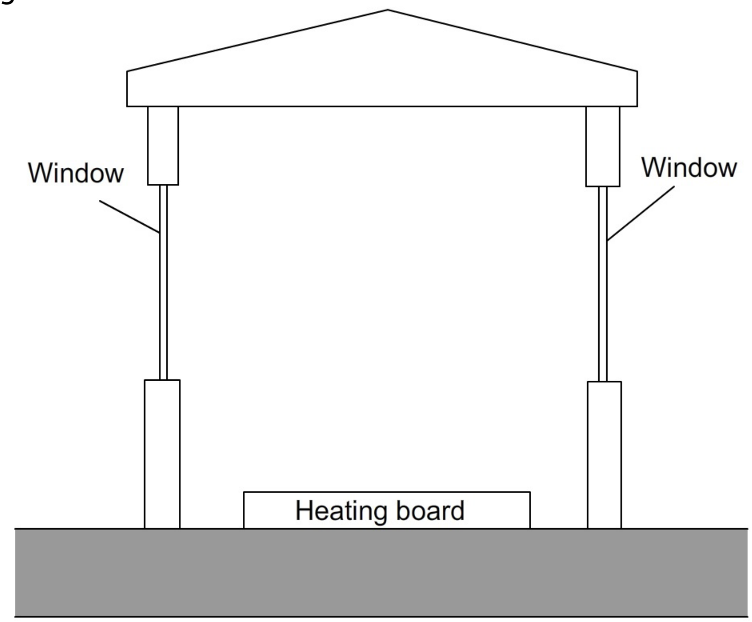
## 4E: Blowing wind

This model shows a wind blowing across a building. Open Model 4E and follow the instructions, then answer the following questions.

Draw the motion of the air outside the building before you open the windows. What do you notice about air motion right next to the building?




In the same picture above, draw the motion of the air inside the building before you open the windows.

Describe how the motion of the air changes inside the building:

a. when there is a wind and the windows are open.

b. when there is **no wind** and the windows are open.

# Connection to buildings: Convection heat loss

## Application

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

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

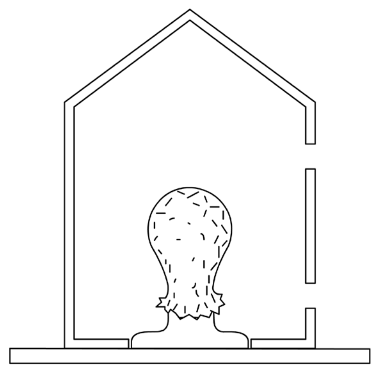
Suggest how you might cut down on these forms of heat loss in a real house.

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

## Summary

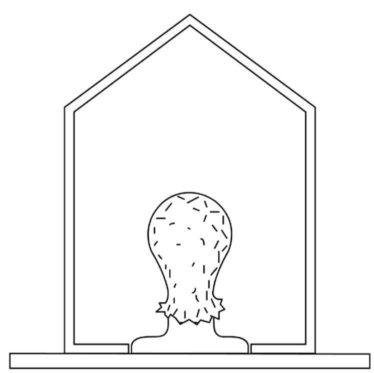
Here is a cross-section of a one-room house. There is a leaky joint near the ceiling and another one near the floor. Suppose the average temperature is 40 °C inside and 20 °C outside.

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



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

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



# Heat Transfer

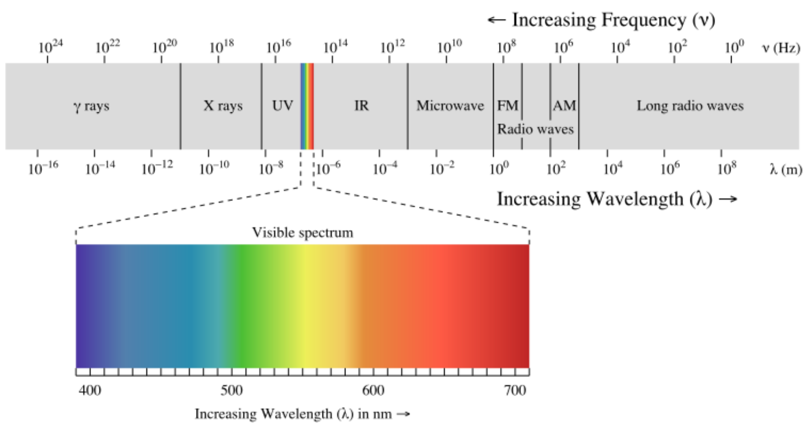
## Radiation

### *Introduction*

Do objects at room temperature give off radiation?

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

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




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

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

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

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Note the video tutorial.

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.

## 5A: Radiation energy depends on temperature

Energy2D

This model shows two objects at different temperatures that are giving off electromagnetic radiation. Open Model 5A and follow the instructions, then answer the following questions.

Describe the effect of temperature on the intensity of radiation, and hence its heating effect on objects that absorb it.

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

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

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

## Connection to buildings

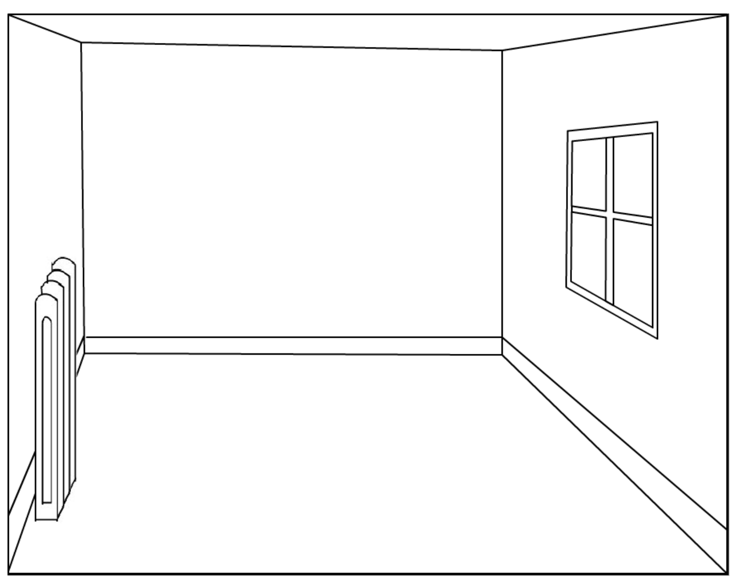
**Application**

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

For example:

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

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



# Heat Transfer

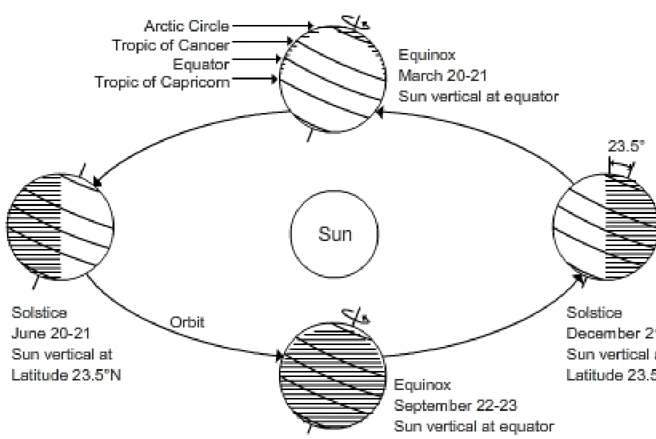
## Energy from the Sun

### *Introduction*

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

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

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




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

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

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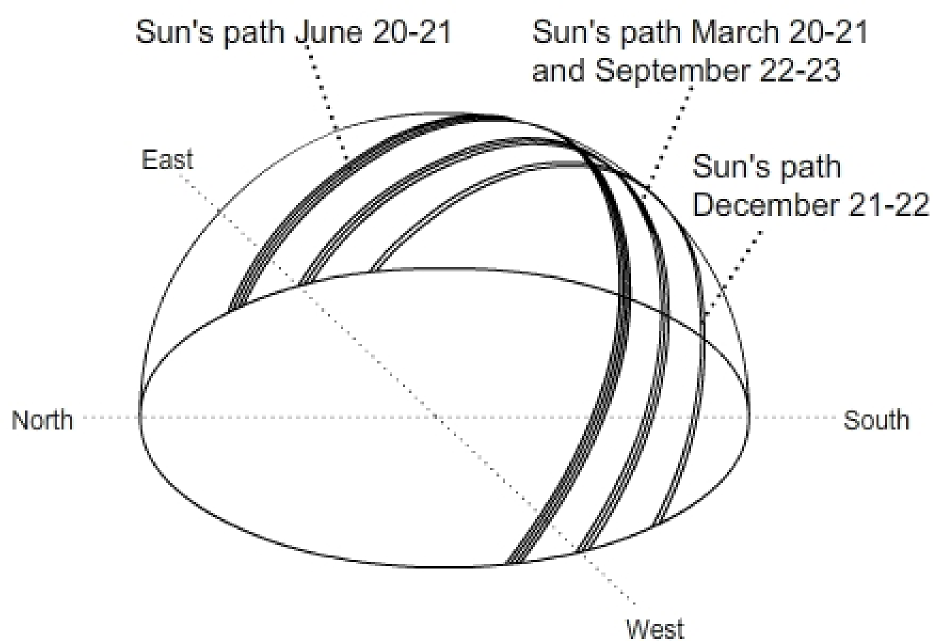
Here is a diagram of the sun's path in the sky at different times of the year. It is roughly correct for a northern latitude of 40°. Note the three lines showing the sun's path. One is the summer solstice, one is the spring and fall equinoxes, and one is the winter solstice.

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



## Where is the sun?

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

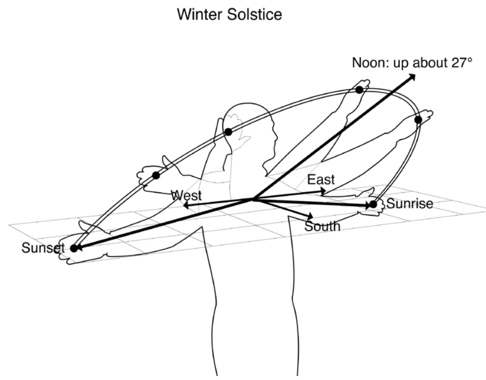
a) At the equinox at noon, the angle of the sun above the horizon is (90° minus the latitude). For example, at the equator this is 90°; at the pole this is 0°.

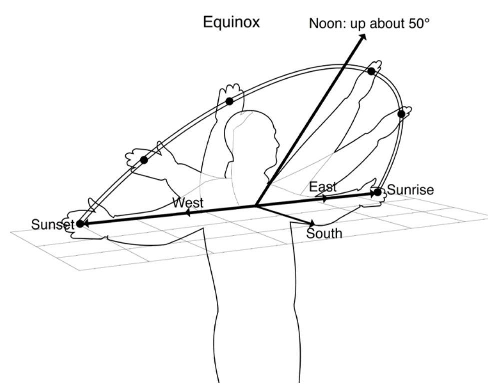
b) At the two solstices, the angular height of the sun at noon either increases or decreases by 23.5°– the tilt of the earth's axis – compared to the equinox.

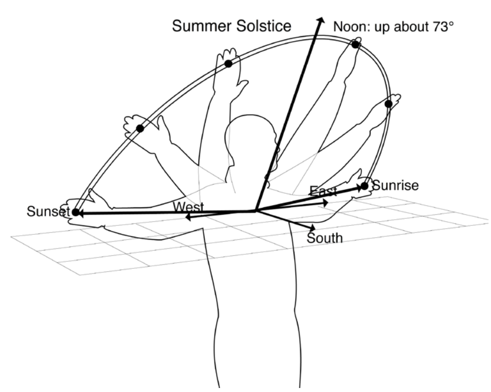
c) For the length of the day, do some Internet research. Many sites give the times of sunrise and sunset. (For 40°N, daylight is about 3 extra hours in summer and 3 fewer hours in winter.)

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

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



# Heat Transfer

## Energy Detective

### *Introduction*

As a wrap-up, use the model to explore heat flow in a whole house model. You can move temperature sensors around, just as you would with real temperature sensors in the standard house model. The advantage of a computer model is that you can change features and make measurements very quickly. And you can also add as many sensors as you want. On the other hand, a model is never just like the real world.

### 6A: A well-insulated house vs. a poorly insulated house

**Energy2D**

Use the model to investigate the quality of construction of the two houses. Open Model 6A and follow the instructions. Then answer the following questions.

Which house required more power to keep warm, A or B? Explain how you figured this out.

Go back to the model and do more tests to answer these two questions. Recall that the rate of heat loss is proportional to the difference between inside and outside temperatures.

1. How much more power, roughly, does the less energy-efficient house require (for example, 1 ½ times, 2 times, 3 times, 4 times as much power)?

2. What is the ratio of high heater power to low heater power?

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## 6B: Where does this house lose heat the most?

Use the model to investigate the quality of construction of different parts of the model house. Open Model 6B and follow the instructions. Then answer the following questions.

Describe the method and measurements you used to find the poorly insulated places.

Fill out the following table with results from Model 6B.

| Results from Model 6B | | |
|---|---|---|
| Building section | Insulating quality (great, good, fair, poor) | Evidence (measurements) |
| A | | |
| B | | |
| C | | |
| D | | |
| W | | |
| R | | |
| G | | |

## 6C: Discover a vertical temperature gradient

Energy2D

You have probably noticed that houses are often warmer near the ceiling than near the floor, and warmer upstairs than downstairs. This model shows the effect of natural convection in a house. Open Model 6C and follow the instructions. Then answer the following questions.

| Results from Model 6C | | |
|---|---|---|
| Thermometer | Temperature with ceiling | Temperature without ceiling |
| T1 | | |
| T2 | | |
| T3 | | |

Describe the effect of removing the ceiling.

Many modern houses have living rooms in two-story spaces, so that the ceiling is 12 or more feet high. Explain why this kind of space is difficult to heat, and what you could do about it.

## 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?