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)**
ΔT = **temperature difference across the material**
L = **thickness of the layer (m)**
A = **area of the material (m²)**
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:

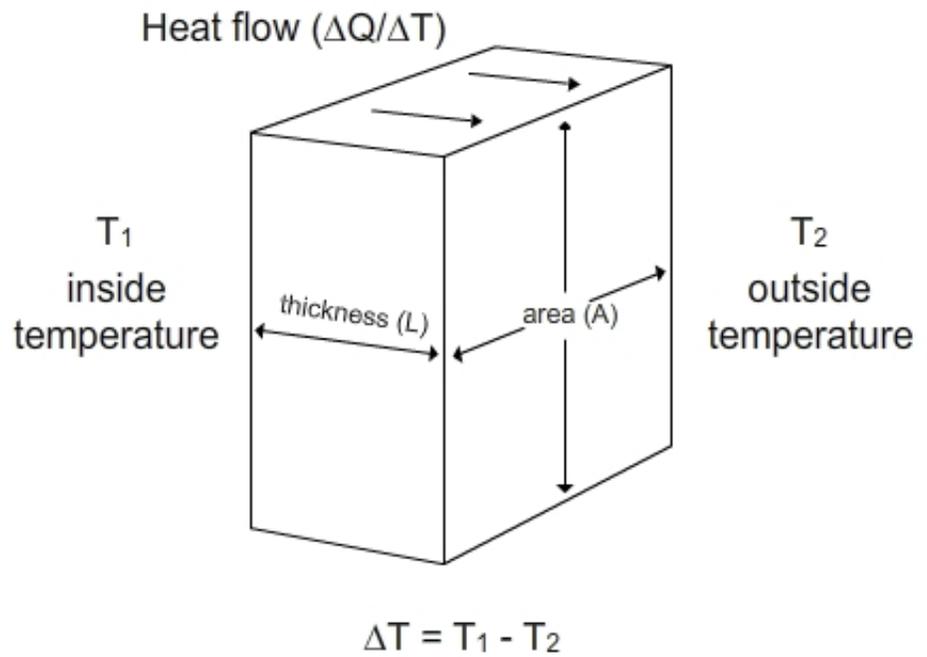$$\Delta Q / \Delta t = (Q_2 - Q_1)/(t_2 - t_1)$$

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

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.

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

To download Energy2D software, go to http://energy.concord.org/energy2d/

To run the models in this chapter, go to http://energy.concord.org/htb

Note the video tutorial.

Heat flow ($\Delta Q/\Delta T$)

T$_1$
inside
temperature

thickness (L)

area (A)

T$_2$
outside
temperature

$$\Delta T = T_1 - T_2$$

Factors that affect heat conduction through a solid material.

3A: Heat conduction through materials

Energy2D

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.

Energy2D

3B: The effect of thermal conductivity

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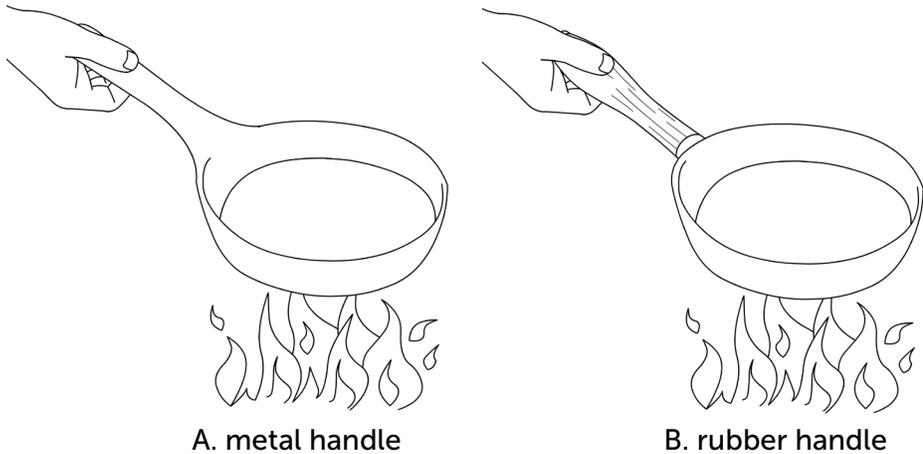
When you cook with a frying pan, you may notice that a rubber handle stays cooler than a metal handle.

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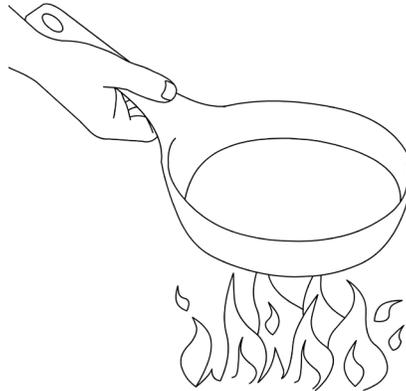
Which material has a greater conductivity, the upper or lower material? What is your evidence from the model?

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

3C: The effect of wall thickness
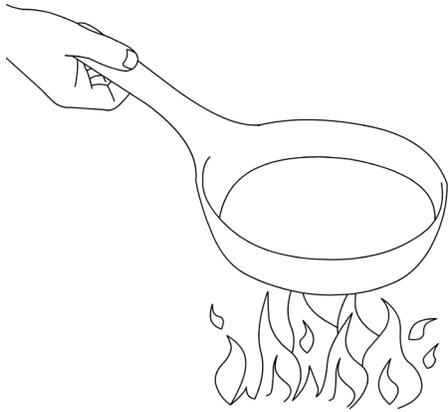
A. hand farther up the handle   B. hand closer to the pan

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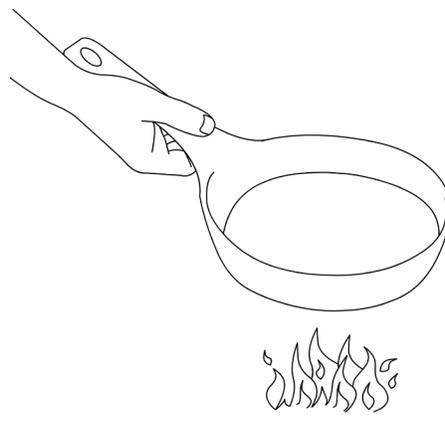
Compare the two cases. How does wall thickness affect heat flow?

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

3D: The effect of temperature difference
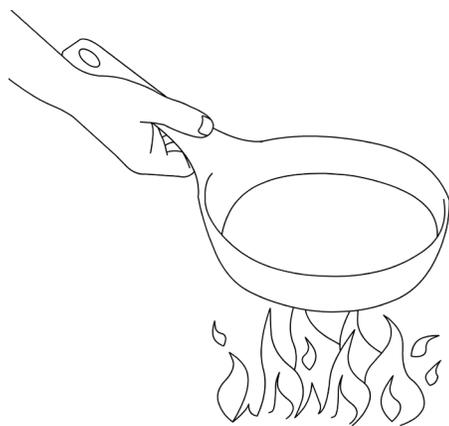
A. more intense heat source   B. less intense heat source

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

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)?