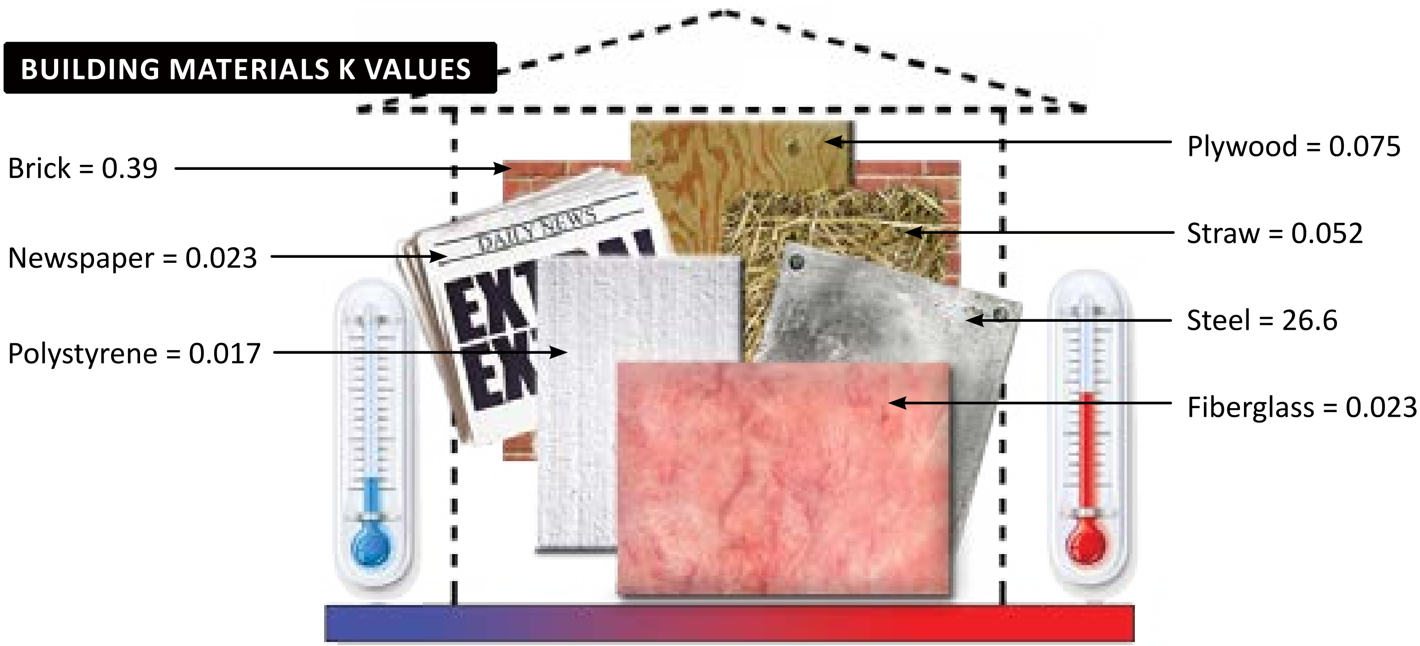
KSB* 2

(*KNOWLEDGE AND SKILL BUILDER)

CONDUCTIVE HEAT FLOW



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SCHOOL: ____

DATE: ____

Hofstra University Center for
Technological Literacy
Simulations and Modeling for Technology Education

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In this KSB, you will learn how heat flows through a material by conduction. In doing so, you will learn how to design your shelter to limit the heat that flows from the warm area inside, to the cold area outside. **KSB 2 should take you two to three periods of class time.**

(Please be sure to attach all your drawings and your calculations after the last page.)

IN THIS KSB, EACH OF THE FOLLOWING KEY IDEAS WILL BE EXPLAINED CLEARLY; FOR NOW, JUST READ THEM OVER BRIEFLY.

KSB 2A: Heat flows from hot to cold through a material by conduction.

KSB 2B: Since heat is transferred from a hot temperature (T_h) to a cold temperature (T_c) through a flat surface, reducing the amount of surface area reduces heat transfer.

KSB 2C: Different materials conduct heat at different rates depending upon their thermal conductivity. Thermal conductivity is symbolized by the letter (**k**).

KSB 2D: As the thickness of a material increases, the heat flow through it decreases.

POINTS TO PONDER

STOP HERE FOR A MINUTE AND READ THE FOLLOWING NOTES!

Note 1: Heat flow is represented by the letter (**Q**).

Note 2: The temperature difference between hot and cold temperature ($T_h - T_c$) is often referred to as the change in temperature, and is written as **ΔT**.

In case you were wondering the **Δ** symbol is the Greek letter “delta”. This symbol is also used as the Delta Airlines logo.

DELTA

Photo Courtesy of Delta Airlines

There is one more key idea (KSB 2E) to learn. It puts all the other key ideas together in a mathematical relationship (a formula). Don’t worry about the use of symbols; they will all be explained. And look – the formula just involves simple multiplication and division.

You’ll have a chance to use this formula to calculate the heat flow through your shelter’s walls with your teacher’s help.

KSB 2E: The formula that relates heat flow (**Q**) to its determining factors is:

$$Q = kA(T_h - T_c)/L$$

THIS FORMULA WILL BE EXPLAINED WELL. DON’T LET THE SYMBOLS BOTHER YOU.

NOW LET'S LOOK AT EACH OF THESE KEY IDEAS IN MORE DETAIL:

KSB 2A : HEAT (**Q**) FLOWS FROM HOT (**T_H**) TO COLD (**T_C**) THROUGH A MATERIAL BY ***CONDUCTION***.

Note: Heat flow is represented by the letter (**Q**).
The temperature difference ΔT between hot and cold temperature (**T_h -T_c**) is referred to as the change in temperature, and is often written as **ΔT**.

Since you are building a survival shelter and the outside temperature is very cold, you will have to design the shelter to keep the heat from flowing from the warm inside areas, to the colder outside area.

The diagram on the right (*Figure 1*) shows how heat flows from hot to cold through a wall. Your shelter will have to do a good job of keeping the heat inside.
The heat travels through the wall by conduction. Conduction refers to the transfer of heat energy through matter (in this case, the wall). It occurs when one side is warmer and one side is cooler.

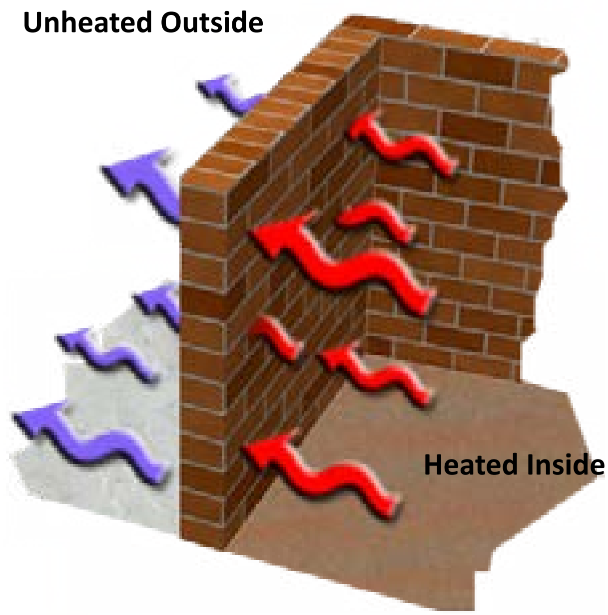

Figure 1: Conduction through a wall

HOW DOES CONDUCTION HAPPEN?

As you probably know from your study of science, all matter is made up of atomic particles. Atomic particles all vibrate to some extent. Heat energy makes the particles vibrate faster. At the warmer side of an object, the particles vibrate more rapidly (*see Figure 2*). These rapidly vibrating particles collide with other nearby particles and cause them to vibrate faster too. In this way, heat energy is transferred from warm areas to nearby cooler areas (which then also become warmer). The heat transfer continues until both sides are at the same temperature.

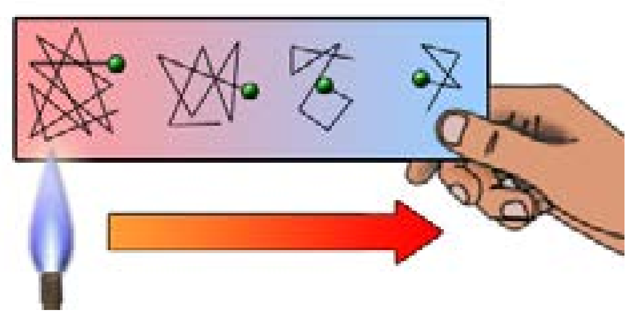

Figure 2: Heat flows from hot to cold

Click on the link below to see an animation that shows how heat flows from warm to cold.
http://www.phy.cuhk.edu.hk/contextual/heat/hea/condu/conduction_e.html

Here are some examples that you will be familiar with:

(1) When you use a stove to heat food in a metal pot, the bottom of the pot is in contact with the heat source. The atomic particles in the bottom of the pot begin to vibrate faster. Their increased energy is transferred to the neighboring atoms ultimately heating the inside of the pot. The heat energy from the inside of the pot is transferred, in a similar way, to the food that is being cooked, as the food too conducts heat (although not as well as the metal pot).

(2) When you hold a cup of hot liquid in your hand, you feel the heat that is transferred from the hot liquid to the cup, and then from the cup to your hand. Again, this occurs through the transfer of energy from warm areas to colder areas.

Let's think about how this relates to your shelter design. Clearly, if heat is transferred from the inside of a shelter where it's warm, to the cold outside, it could get pretty uncomfortable for people in the shelter who want to stay warm. It's really important, therefore, to make sure that the shelter is designed to minimize the heat loss to the outside.

HERE IS SOME GUIDANCE FOR YOU:
Heat flow is represented by the letter (**Q**).
The temperature difference (**ΔT**) between hot and cold temperature is $T_h - T_c$. Don't let these symbols confuse you; it's really quite simple. Remember that T_h is the hot temperature and T_c is the cold temperature.

If the temperature inside the shelter (T_h) is 70°F and the temperature outside (T_c) 30° F, the temperature difference (**ΔT**) is 40° F. That's all there is to it.

CHECK YOUR UNDERSTANDING

Figure out **ΔT** for each set of temperatures in the table to the right. **Write in your answers.**

T_{HOT}	T_{COLD}	$\Delta T\ (T_H - T_C)$
T_H = 200° F	T_C = 70° F	
T_H = 100° F	T_C = 60° F	
T_H = 68° F	T_C = 32° F	
T_H = 60° F	T_C = -10° F	

MATH AT WORK: Q α ΔT

Q is proportional to ΔT. Heat flow is directly proportional to the temperature difference between hot and cold areas. When ΔT is great, the rate of heat flow is faster. If ΔT is small, the rate of heat flow is slower. No matter what the rate, heat continues to flow from warm areas to cold areas until both areas are at the same temperature. This graph (*Figure 3*) shows heat flow through a 1" thick piece of fiberglass that has a 1 ft x 1 ft cross sectional area.

NOTE: The **α** symbol is the Greek letter (lower-case) for "alpha". Here it means "is proportional to".

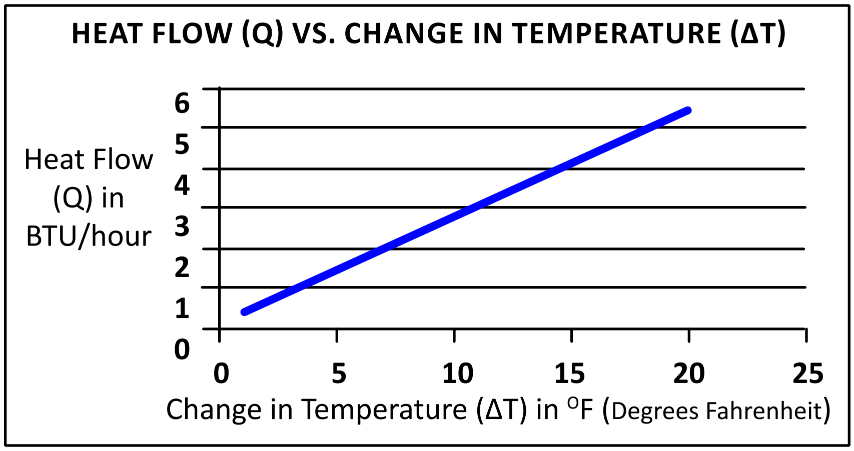

Figure 3: Graph of Heat Flow through 1" of fiberglass

QUICK ANALYSIS QUESTION: (MULTIPLE-CHOICE)
As the temperature difference (ΔT) between hot and cold areas increases, the conductive heat flow through the material does what? (**Circle one answer below**)

A) Increases B) Decreases C) Remains the Same

THINK LIKE AN ENGINEER

People are pretty good heat generators. An average adult, doing little or no work, generates about 100 Watts just as a result of normal body functioning. (To get an idea of that amount of heat, think about the heat generated by a 100-Watt light bulb.) 100 Watts equates to about 340 BTU per hour. One BTU (British Thermal Unit) is the amount of heat needed to raise one pound of water one degree Fahrenheit.

When you build your shelter, you'll have to make sure that the total heat generated by the body heat of your four team members is greater than or equal to the heat that is lost through the walls (by conductive heat transfer) when the inside temperature is 45° F and the outside temperature is 25° F. If total body heat is less than the heat lost through the walls at this critical point, the temperature inside your shelter will continue to fall and hypothermia will result.

IN THIS SECTION (KSB 2A), YOU LEARNED ABOUT THE RELATIONSHIP BETWEEN HEAT FLOW AND THE TEMPERATURE DIFFERENCE BETWEEN HOT AND COLD AREAS. IN THE NEXT SECTION (KSB 2B), YOU WILL LEARN ABOUT THE RELATIONSHIP BETWEEN HEAT FLOW AND THE SURFACE AREA OF A STRUCTURE.

KSB 2B: SINCE HEAT IS TRANSFERRED FROM HOT (T_H) TO COLD (T_C) THROUGH A FLAT SURFACE AREA (LIKE A WALL) REDUCING THE AMOUNT OF SURFACE AREA REDUCES HEAT TRANSFER.

Think about this...
What happens when you go out into the cold? Your body heat is transferred from your inner core to the outside air through your skin (your body's surface). You will have to design your shelter to keep the heat from flowing from the warmth inside to the cold outside.

POINTS TO PONDER

In 1877, Joel Allen observed that the length of arms and legs in warm-blooded animals relates to the temperature of their environment. Members of the same species (for example humans) who live in warm climates tend to have longer limbs than members of that species who live in colder climates. This rule, called Allen's rule, is based on heat flow. Longer limbs offer more surface area and lose heat more easily than shorter limbs which have less surface area and are more effective in maintaining heat. Why do you think that the Inuit people, who live in cold northern climates, tend to have stockier bodies with shorter limbs than the Masai people who live in warm African climates and tend to have longer limbs and be taller?

The rate of heat flow from the warm area inside the shelter to the cold areas outside has a lot to do with the surface area of the shelter. If the shelter has a large surface area, the rate of heat loss is faster. If the surface area is smaller, the rate of heat loss is slower.

Remember, from KSB 1 that the shape matters. Some shapes have more surface area than other shapes even though they can contain the same volume. In designing a shelter, you want to be able to house the four team members, but at the same time, minimize the surface area of the shelter.

MATH AT WORK: Q α A
Q is proportional to A. Heat flow is directly proportional to the surface area of a structure. That means if A goes up, Q goes up; if A goes down, Q goes down. If you want to minimize Q, design your shelter with the smallest surface area possible.

SURFACE AREA IN USE

Figure 4: Heatsink on Graphics Card

Graphics cards in computers can use the same power as that of a 150 Watt lamp. With so much power running through today's integrated circuits, enormous amounts of heat are created. This heat can kill these devices and likely cause your computer to crash if they are not properly cooled. Cooling can require noisy parts, like fans, or it can be done using materials that dissipate the heat quietly such as the as the heatsink in the accompanying photograph (*Figure 4*). A heatsink lowers the temperature of whatever it is attached to by increasing the total surface area, which in turn boosts the devices' ability to dissipate heat. Heatsinks typically do this with fins. Each fin has its own surface area and all the fins together have a lot of surface area through which heat can dissipate.

From: Don Woligroski, "Graphics Beginners' Guide, Part 1: Graphics Cards" (07/24/2006)
http://www.tomshardware.com/reviews/graphics-beginners,1288.html
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Page 6, "Cooling Devices."
http://www.tomshardware.com/reviews/graphics-beginners,1288-6.html

CHECK YOUR UNDERSTANDING

In the space below, describe how surface area affects conductive heat flow.
Use a complete sentence to explain the relationship below.

KSB 2C: DIFFERENT MATERIALS CONDUCT HEAT AT DIFFERENT RATES DEPENDING UPON THEIR THERMAL CONDUCTIVITY. THERMAL CONDUCTIVITY IS SYMBOLIZED BY THE LETTER (**K**).

You learned (in KSB 2A) that heat energy is transferred from warm areas to cooler areas when rapidly vibrating particles in hot areas collide with other nearby cooler particles. The increased thermal energy causes the cooler particles to vibrate faster too and become warmer.

POINTS TO PONDER

The speed of the transfer of heat energy depends on how tightly packed the atomic particles are in a particular material (the density of the material). Because metals have high densities, they are good conductors of heat; other materials (wood, for example), are less dense and are not such good conductors of heat.

Why do you think liquids are generally not good heat conductors and why are gasses (like air) among the worst conductors of heat?

WRITE YOUR ANSWER HERE.

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CHECK YOUR UNDERSTANDING

From your own experience, **put a check** next to the materials in this list that you think are good or poor conductors of heat. **Then give an example that justifies your decision.**

Material	Good Conductor	Bad Conductor	Example from Your Own Experience
Steel	☐	☐	
Aluminum	☐	☐	
Wood	☐	☐	
Plastic (e.g. Styrofoam ™)	☐	☐	
Air	☐	☐	
Ceramics (glass, clay)	☐	☐	
Paper	☐	☐	

HERE IS SOME GUIDANCE FOR YOU: As you know from your own experience, some materials are better heat conductors than others. **Thermal conductivity** is a property of a material that indicates its ability to allow heat to flow through it. The thermal conductivity of a material is referred to as its **k VALUE**.

A material's thermal conductivity depends upon **what the material is made from**. As examples, a piece of aluminum always has the same thermal conductivity as another piece of aluminum and a piece of glass always has the same thermal conductivity as another piece of the same kind of glass. The same is true for every material.

Better heat conductors have **high thermal conductivities** (high k values) and good heat insulators have **low thermal conductivities** (low k values). For example fiberglass (a poor heat conductor) has a low k value (0.023) while aluminum (a good heat conductor) has a high k value (144.5).

The accompanying table (*Figure 5*) shows some examples of common materials and their k values. You can see that *metals* have much higher k values than non-metallic materials. The materials with the lowest k values make the poorest conductors of heat, and therefore are used as insulation to prevent heat loss. Some excellent insulators are cellulose, fiberglass, and expanded polystyrene (commonly called Styrofoam™). The best heat insulator on the list is *air* (not surprisingly – it's a gas with very low density); and one reason cellulose, fiberglass, and Styrofoam™ are such good insulators is that they contain many pockets of air mixed in with their core material.

(Thermal Conductivities in BTU/hour-ft-deg F)			
MATERIAL	**k VALUE**	**MATERIAL**	**k VALUE**
Air	0.014	Paper	0.029
Aluminum	144.5	Polyethylene	0.24
Brass	62.99	Polystyrene (Styrofoam™)	0.017
Brick	0.39	Polyvinylchloride (PVC)	0.11
Cellulose (loose fill made from newspaper)	0.023	Rubber	0.09
Concrete	0.24	Silver	247.91
Cotton	0.017	Steel	26.6
Copper	236.9	Straw	0.052
Fiberglass	0.023	Urethane foam	0.012
Glass	0.61	Wood (balsa)	0.023
Gold	183.2	Wood (pine)	0.075
Hardboard	0.08	Wood (plywood)	0.075
Iron (cast)	31.78	Wood (oak)	0.098
Newspaper (cellulose)	0.023	Wool	0.04
Nylon	0.14	Zinc	67.04

Figure 5: Table of k Values of some Common Materials

MATH AT WORK: Q α k

Q is proportional to k. Heat flow is *directly proportional* to the thermal conductivity of a material. That means if k goes up, Q goes up; if k goes down, Q goes down. If you want to minimize Q, design your shelter using materials with the lowest k values possible.

Since some materials are better heat insulators (have *lower thermal conductivities*) than others, think about which materials can be used as insulation in construction projects. Identify structural insulation materials (those that are self supporting); and non-structural materials (those that are used only as fill).

THINK LIKE AN ENGINEER

Name six good insulation materials. Circle those that are structural materials and put a rectangle around those that are non-structural.

1.______________________________

2. ______________________________

3. ______________________________

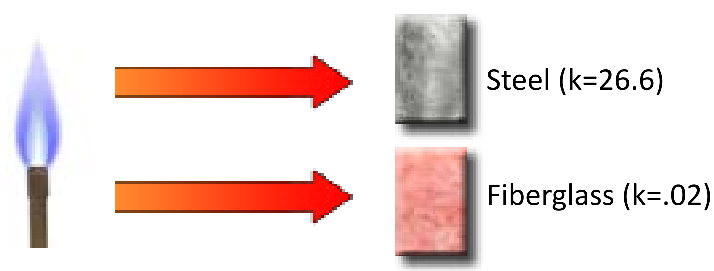
4.______________________________

5. ______________________________

6. ______________________________

CHECK YOUR UNDERSTANDING

In the diagram to the right, two materials are being heated by the same heat source. The materials are exactly the same size, but one is made from steel, the other from fiberglass.
Using this example, explain (**using a complete sentence**) how the different materials will affect conductive heat flow.



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THERMAL CONDUCTIVITY IN USE

For a great example of how the thermal conductivity of a material is used to cool computer graphics cards, click on:

http://img.tomshardware.com/us/2006/07/24/graphics_beginners_guide/heatpipe.gif

Some devices like graphics processor and memory chips in computers are so small that a bulky heat sink will not work properly as there is not much heat conductive material touching the electronic device. In such cases, a heat pipe (*Figure 6*) helps to transfer heat from a hot spot to a more substantial heat sink.

Typically, a heat conductive metal plate is placed onto thegraphics chip. The heat pipe is directly attached to this metal plate and transfers heat to a heat sink at the other end of the pipe, where the heat can be dissipated easily.

Figure 6: CPU Heat Sink front view

From: Don Woligroski, "Graphics Beginners' Guide, Part 1: Graphics Cards" (07/24/2006)
http://www.tomshardware.com/reviews/graphics-beginners,1288.html
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Page 6, "Cooling Devices."
http://www.tomshardware.com/reviews/graphics-beginners,1288-6.html

KSB 2D: HEAT FLOW DECREASES WITH INCREASING THICKNESS.

When you wear a jacket to keep you warm in cold weather, the jacket likely has insulation designed into its construction. A ski jacket is a good example. Insulation in the jacket can be made from wool, goose down, or a synthetic fiber like Gortex ™. The thickness of the insulation determines how well it minimizes heat transfer from your body to the outside air. The greater the thickness of the insulation, the better job the jacket does in keeping you warm.

A LITTLE GUIDANCE FOR YOU...
When calculating heat flow, the thickness of a material is symbolized by the letter (**L**).

The same is true when you use a sleeping bag. Thicker amounts of insulation will limit your body's heat loss. The ideal insulation would be a fairly thick piece of material that has a low k value.

POINTS TO PONDER

Remember what you've learned about fractions: if the numerator of a fraction stays the same but the denominator of that fraction gets larger, the value of the fraction decreases. If you have 1/2 a pizza, you have a lot more to eat than if you have 1/8 of a pizza. If the numerator stays the same, the amount you have to eat is *indirectly proportional* **to the denominator of the fraction of the pizza that you have to eat. Look at these fractions:**

1/2 1/3 1/4 1/5 1/6 1/7 1/8 1/9 1/10

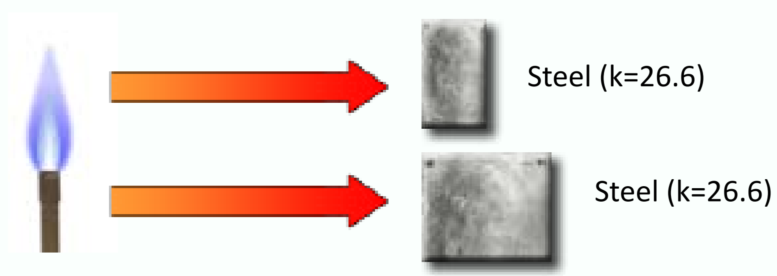
You can see that as denominators get larger, the value of the fractions get smaller. The relationship between heat flow and the thickness of a material is similar: they are also *indirectly related*. The greater the thickness of a material, the lower the amount of heat flow.

MATH AT WORK: $Q \propto 1/L$
Q is indirectly proportional to L, the thickness of a material. That means if L goes up, Q goes down; if L goes down, Q goes up. If you want to minimize Q, design your shelter using thicker insulation materials.

CHECK YOUR UNDERSTANDING

In the diagram below, two materials are being heated by the same heat source. The materials are made from the same material (in this case, steel). However, one is thicker than the other.

Using this example and **in the space below the diagram**, explain how the thickness of a material will affect conductive heat flow.



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KSB 2E: THE FORMULA THAT RELATES HEAT FLOW (Q) TO ITS DETERMINING FACTORS IS:

$Q = KA (\Delta T) / L$

Let's put together what we've learned so far in this KSB. Recall that there were four relationships that we studied:

Q is proportional to ΔT: Heat flow is directly proportional to temperature difference.

Q is proportional to A: Heat flow is directly proportional to the surface area of a structure.

Q is proportional to k: Heat flow is directly proportional to the thermal conductivity of a material

Q is indirectly proportional to L: Heat flow is indirectly proportional to the thickness of a material.

The formula for conductive heat flow is a simple algebraic equation that enables you to determine if the shelter you design to provide refuge from the cold, will provide an inside temperature that allows the inhabitants to be comfortable. ***Don't let the algebra scare you!*** The math involves ONLY simple multiplication and division once you substitute numbers for letters.

SOLVING FOR CONDUCTIVE HEAT FLOW REQUIRES USING THIS EQUATION:

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

The formula shows exactly what we've learned – and puts the relationships together in one neat mathematical expression. Look at the formula and you can see that Q is directly proportional to k, A, and ΔT, and indirectly proportional to L.

In the formula:

Q = Heat flow (in BTU/hour);

k = Thermal conductivity of the material.

A = Area of surface through which heat is conducted (in square feet);

ΔT = Temperature difference between hot and cold (in degrees F);

L = Thickness of insulation material (in feet). (Note that thickness is measured in feet, not inches.)

MATH AT WORK: CALCULATING HEAT FLOW.

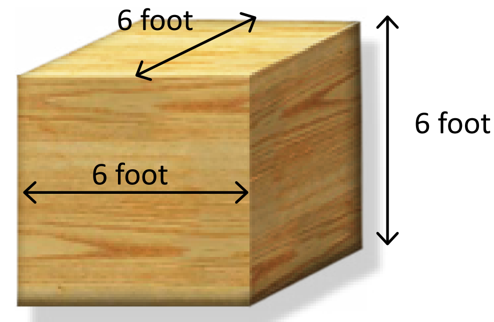

Figure 7: **1" thick plywood box**

Using the heat flow formula, find the number of Btu/hour that will be necessary to maintain an inside temperature of 70° F if the outside temperature is 25° F. Assume a cubic structure (*Figure 7*) 6' on each side and that the structure is made of plywood that is 1" thick.

HOWEVER, since the bottom of the structure rests on the ground, most of the heat flow is through the five other sides (the four walls and the top). So, for our purposes, we will neglect the **heat flow through the bottom**. The effective SA (surface area) of the cubic shelter is calculated by multiplying five sides x the SA of one side, or 5 x 36 = 180 ft^2.

1. Start off with the formula **Q = kA (ΔT) / L**

2. Substitute numbers for letters.

   a. From the table of k values in KSB 2C, you know that the k value for plywood is 0.075.

   b. From KSB 1, you will remember that the formula for the surface area (SA) of a cube is SA = $6s^2$ but for our cubic structure, **we will only consider the heat loss from the four sides and the top**; so:

      SA = 5 x 36 = 180 ft^2.

   c. Now for the temperature difference;
      $\Delta T = T_h - T_c$
      = 70 – 25
      ΔT = 45° F

   d. Also be sure to remember that thickness, L, is measured in feet, not inches; so, a 1" thickness of plywood equals 1/12 foot or about 0.083 feet.

Q = k A (ΔT) / L

3. Now, plug in the numbers and solve: Q = (.075) (180) (45) / .083

4. So, Q = 7,319 BTU/hour. That means that every hour, the shelter loses 7319 BTU (when ΔT = 45° F). So in order to ensure that the temperature inside the shelter does not fall below 70° F, we need in internal heat source that generates at least 7,319 BTU/hour.

CHECK YOUR UNDERSTANDING

Your Turn! Figure out how much heat is lost through the walls of a cabin shaped like a cube. It is made from oak boards that are 2" thick with surfaces that measure 10 ft. x 10 ft. The inside temperature of the cabin is 68° F and the outside temperature is 15° F. (Remember to look up the k value for oak, and to convert the thickness to feet.) The answer you should get is **15,582 BTU/hour**.

SHOW YOUR WORK HERE (Q = kA (ΔT) / L)

THINK LIKE AN ENGINEER

Remember that in KSB2a, you learned that a human being generates about 100 watts, or 340 BTU/hour. Your four team members would then generate 4(340) or 1,360 BTU/hour. If the heat loss that you just calculated in the first sample problem is 7,319 BTU/hour, **your team will freeze!** (Since the heat loss exceeds the heat generated.) What are several things you might do to reduce the heat loss in order to survive? **Write the them down below.**

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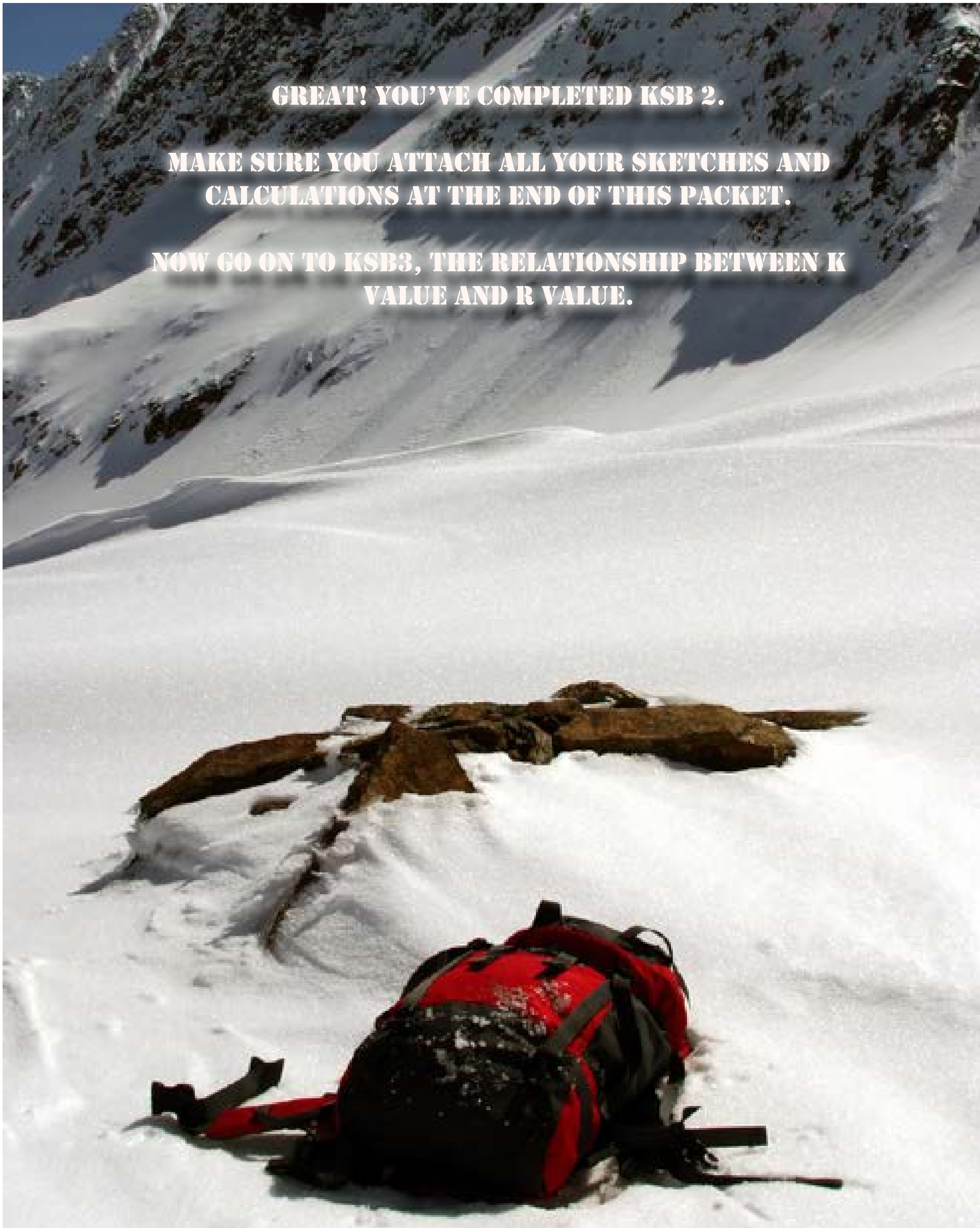
GREAT! YOU'VE COMPLETED KSB 2.
MAKE SURE YOU ATTACH ALL YOUR SKETCHES AND CALCULATIONS AT THE END OF THIS PACKET.
NOW GO ON TO KSB3, THE RELATIONSHIP BETWEEN K VALUE AND R VALUE.