Tuesday April 11

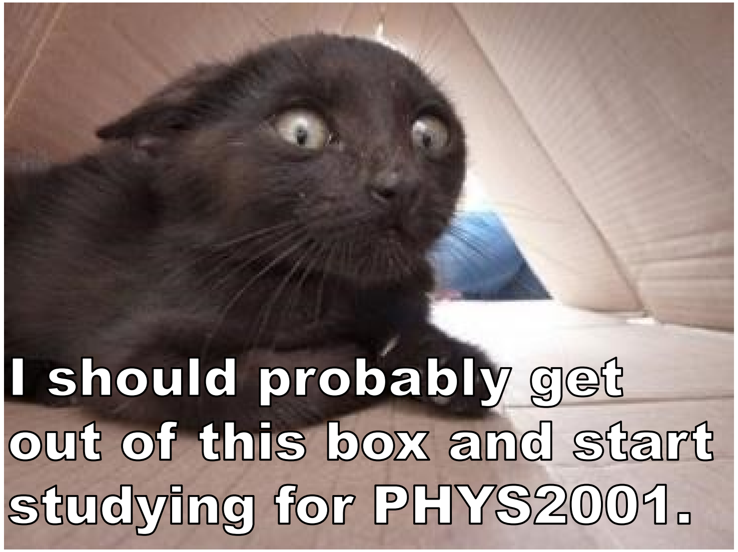
Topics for this Lecture:

- *Thermal Physics*
  - *Temperature & Heat*
  - *Temperature measurement*
  - *Thermal expansion*

- Assignment 13 due Friday
- Pre-class due 15min before class
- Help Room: Here, 6-9pm Wed/Thurs
- SI: Morton 326, M&W 7:15-8:45pm
- Office Hours: 204 EAL, 10-11am Wed or by appointment (meisel@ohio.edu)

- $T_F = (9/5)(T_C) + 32$
- "Temperature" is ***not*** "Heat"
- Thermal linear expansion:
  - $\Delta L = \alpha L_0 \Delta T$ $[\alpha]$ = K-1
- Thermal volume expansion:
  - $\Delta V = \beta V_0 \Delta T$ $[\beta]$ = K-1
  - For solids, $\beta \approx 3\alpha$
- Heat energy flow:
  - $Q=c*m*\Delta T$
  - $Q_{lost} = Q_{gained}$

The **comprehensive** final is in ~2 weeks.



What is the equivalent of 20 degrees C in Fahrenheit?

(A) 11 degrees
(B) 43 degrees
(C) 68 degrees
(D) 132 degrees

20C is about room temperature.

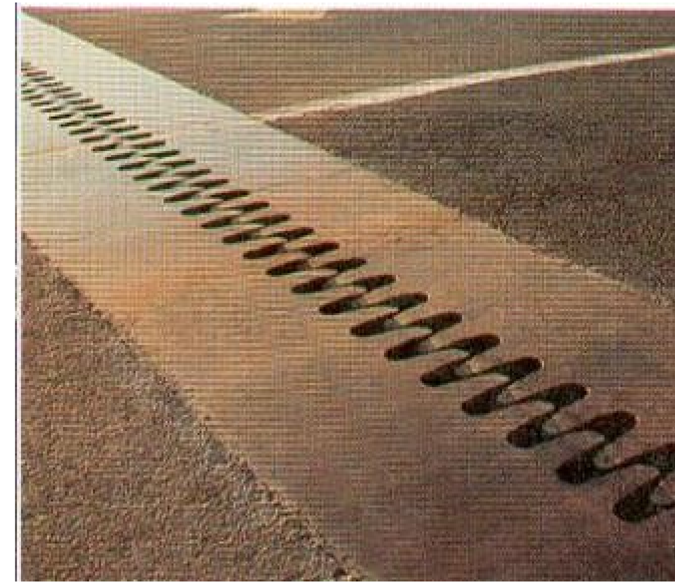
Zero C is freezing,
10C is cold,
20C is nice,
30C is hot.

1. $T_{Fahrenheit} = (9/5)T_{Celsius} + 32$
2. $T_{Fahrenheit} = (9/5)(20) + 32 = 68$

Thermal Physics

Why can we only see warm things in infrared and not cold objects?

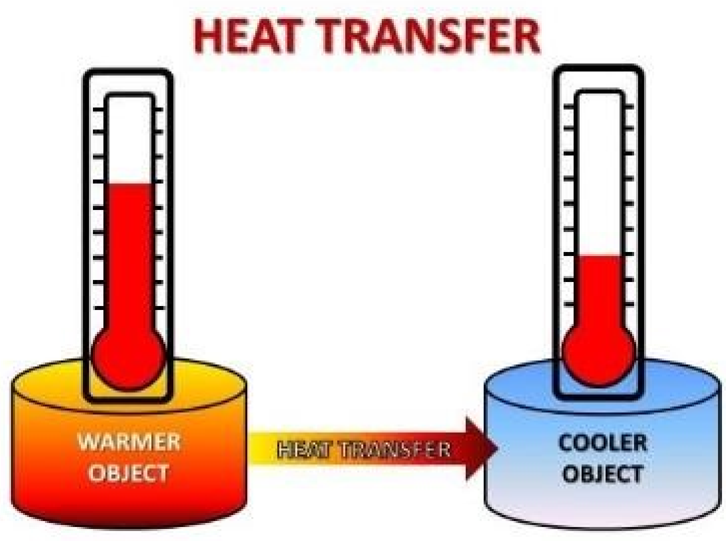
Why do bridges have these sorts of joints?



How much energy does it take to bring water to a boiling temperature?

Temperature & Heat

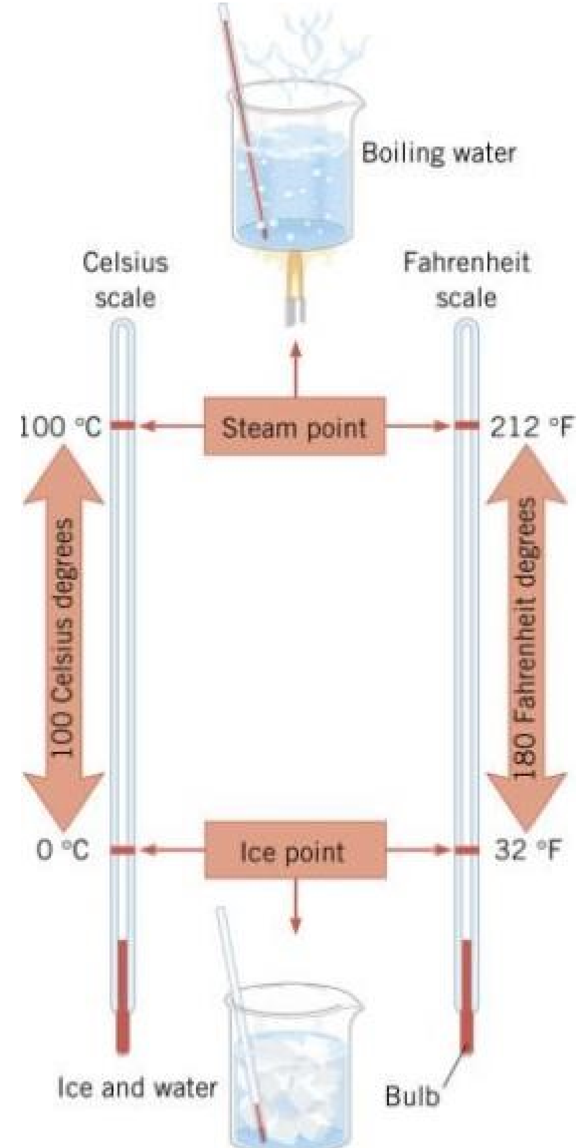
- Temperature:
  - A measure of the internal kinetic energy of atoms & molecules within an object.
  - This is a property of an object.
- Heat:
  - A measure of the transfer of energy between two objects.
  - This is a property of an interaction, not of a single object.
  - Heat is the energy moving from a high temperature object to a low temperature object.



Temperature Scales

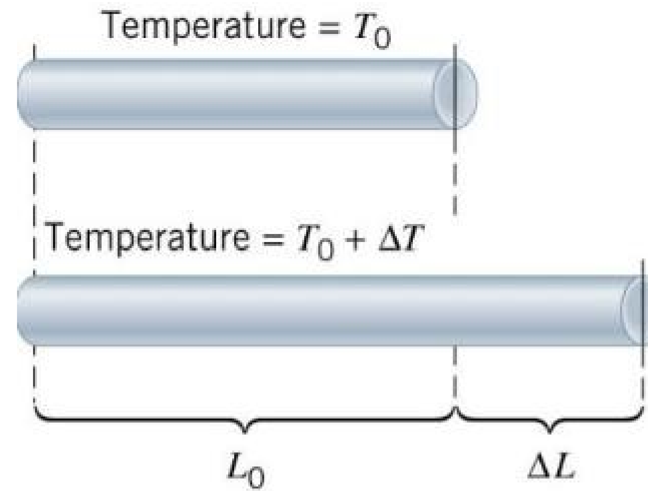
- A few common units are used for temperature:
  - Fahrenheit, Celsius, & Kelvin
- Fahrenheit is related to Celsius by:
  - $T_{Fahrenheit} = (9/5)T_{Celsius} + 32$
  - $\Delta T_{Fahrenheit} = (9/5)\Delta T_{Celsius}$
- Celsius is related to Kelvin by:
  - $T_{Kelvin} = T_{Celsius} + 273.15$

- Zero Kelvin is “absolute zero” (lowest possible T)
- Zero Celsius is the freezing point for water, which is 32 Fahrenheit and 273.15 Kelvin.
- 100 Celsius is the boiling point for water, which is 212 Fahrenheit and 373.14 Kelvin.



Thermal Expansion of Solids: Linear expansion

- Objects expand when their temperature increases.
- The amount of expansion depends on the material properties and is known as the expansion coefficient: α
- α depends on the particular material (and one the phase of matter). SI unit: K^{-1}
- α describes how much an object expands **in a linear dimension** for a given temperature increase
  - $\Delta L = \alpha L_0 \Delta T$
- The fractional change in length is:
  - $\Delta L/L = \alpha \Delta T$
  - **ΔT must be in Celsius or Kelvin**
- Typical α values are (at 20 degrees C):
  - Aluminum, Copper, Silver: ~2×10^{-5} K^{-1}
  - Concrete, Glass, Steel : ~1×10^{-5} K^{-1}
  - Diamond: ~0.1×10^{-5} K^{-1}



This is why you need special joints for, e.g. bridges

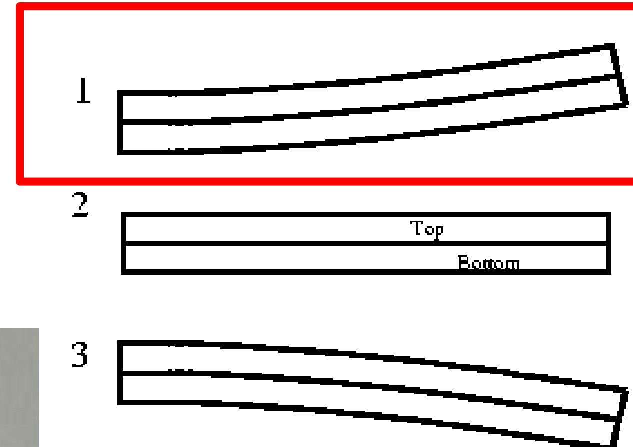
An 0.5m-long rod with a thermal expansion coefficient of $\alpha \sim 10^{-5}\,K^{-1}$ is heated from room temperature (~293K) to the boiling temperature for water (~373K). How much extra length does the rod have after heating?

(A) 4×10^{-6} m
(B) 4×10^{-4} m
(C) 4×10^{-2} m
(D) 4 m

1. $\Delta L = \alpha L_0 \Delta T$
2. $\Delta L = (10^{-5}\,K^{-1})(0.5m)(373K - 293K)$
3. $\Delta L = (10^{-5}\,K^{-1})(0.5m)(80K)$
4. $\Delta L = 0.0004m = 400\mu m$ *This is ~4 human hair widths.*

A bi-metallic strip is composed of one metal sandwiched together with another, so one metal is on top and another metal is on the bottom. If the metal on the top half has a smaller thermal expansion coefficient than the metal on the bottom half, which picture best represents what happens after the bi-metallic strip is heated?

(A) 1
(B) 2
(C) 3



1. $\Delta L = \alpha L_0 \Delta T$
2. The top strip has a smaller α and so it will expand less than the bottom strip.
3. To achieve the extra length on the bottom, without lengthening the top-half by the same amount, the strip is forced to bend upwards.

This is how some of the older spring-based thermostats work. Temperature changes cause the spring to bend, ultimately completing a circuit to turn on/off the heat/AC.

A washer is made of some metal with some thermal coefficient of linear expansion, α.

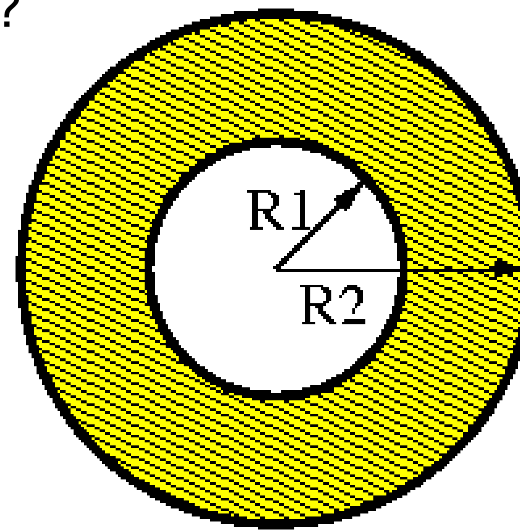
If the washer is heated, what happens to R1 and R2?

(A) R1 decreases, R2 increases

(B) R1 increases, R2 increases

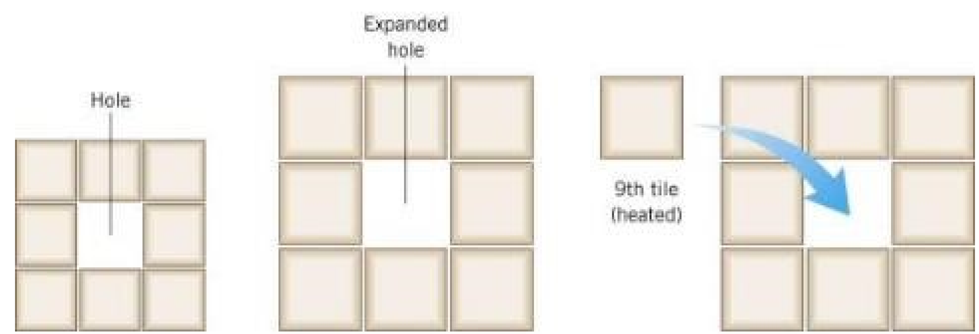
(C) R1 increases, R2 decreases

(D) R1 decreases, R2 decreases



1. $\Delta L = \alpha L_0 \Delta T$
2. This means all linear dimensions increase.
3. The radii are linear dimensions, so both will increase.

For instance, consider what would happen if our washer were made-up of separate square components. All sides would lengthen and "R1" and "R2" would both increase.



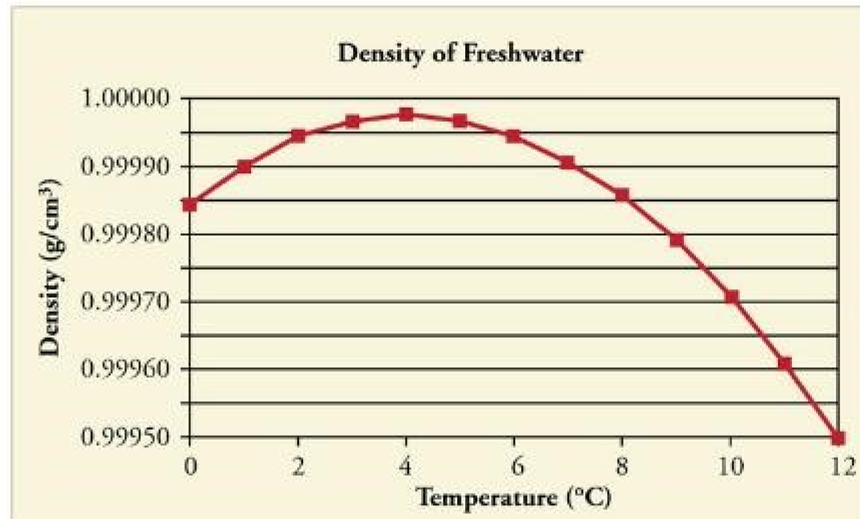
(a) Unheated (b) Heated (c)

Thermal Expansion of Solids: Volume expansion

- Sometimes we want to consider how the volume of an object changes when we heat it. This is the volume expansion
- Volume expansion: $\Delta V = \beta V_0 \Delta T$
- The fractional change in volume is: $\Delta V / V_0 = \beta \Delta T$
- β is the coefficient of volume expansion (SI units: K^{-1})
  - For solids: $\beta \approx 3\alpha$
  - For liquids: More complicated, so look-up in table

Most materials expand in volume when they heat-up. However, water doesn't.

*Note the change in density is **tiny**, so we can usually get away with ignoring it, until the phase-transition to ice happens.



You fill-up your 12-gallon fuel tank in your sedan up to the brim and forget to put on your gas cap. Your friend makes the same mistake after filling-up the 18-gallon fuel tank in her truck to the brim.
It gets really hot outside and the gasoline heats-up.
Who loses the most gas?

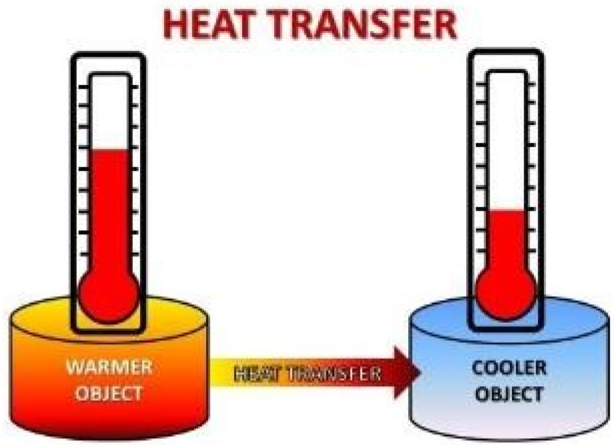
(A) You do

(B) Your friend does

(C) You both lose the same amount

1. $\Delta V = \beta V_0 \Delta T$
2. $\beta * \Delta T$ is the same for both of you.
3. But, V_0 is greater for the 18-gallon fuel-tank for the truck.
4. So, ΔV will be larger for the truck and it will lose more fuel.

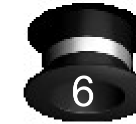
Heat Sect 14.1



- Heat is thermal energy that flows from a high-temperature object to a low-temperature object.
- Heat depends on parameters of a process. These are so-called "state variables"
  - Internal energy (U) of the objects
  - Temperature (T) of the objects

- Your body radiates heat to the surrounding environment as light.
- We see that light in the infrared wavelengths.

Which of these processes will require the most thermal energy?



(A) Raising 1kg of water by 10K

(B) Raising 2kg of water by 10K

(C) Raising 2kg of water by 20K

(D) All the same

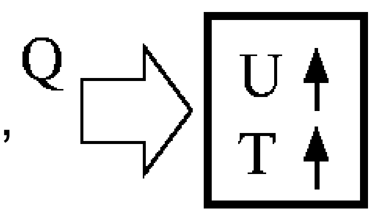
1. More heat will be required to create a larger temperature change.
2. The more material you have to heat-up, the more energy it will take.

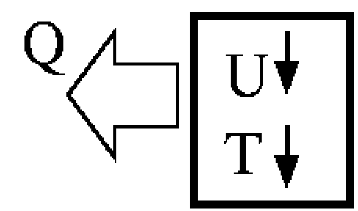
Heat: Heat-energy required to change an object's temperature

- More heat is required to raise the temperature of a larger object.
- More heat is required to induce a larger temperature change.
- The exact amount of heat will depend on properties of the material.
  - These are described the the "specific heat capacity", c
  - c is the amount of energy required to raise the temperature of a given mass of a particular material by a certain temperature change
  - The SI unit of c is: J/(kg*K)
  - Typical values of c are ~100J/(kg*K)

Aluminum is 10X higher than this (which is atypically large ***for a solid****). Meaning it is hard to heat-up. Though, liquid water is even higher.*

- In a formula:
  - $Q=c*m*\Delta T$
- If the temperature of an object **decreases**, it will **release heat** into an environment





- This does not describe phase changes (e.g. liquid water to solid ice)

You want to heat a 1kg block of aluminum and 0.5kg of water by 20K. Which of these processes will require the most thermal energy?

(A) the aluminum block

(B) the water

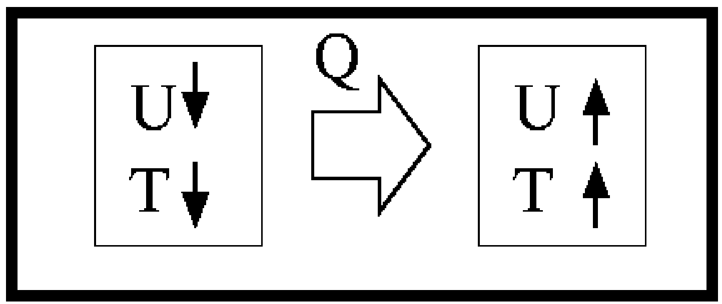
(C) both the same amount of heat

1. $Q = mc\Delta T$
2. $Q_{al} = m_{al}c_{al}\Delta T$ = (1kg)(900J/(kgK))(20K) = 18,000J
3. $Q_{water} = m_{water}c_{water}\Delta T$ = (0.5kg)(4000J/(kgK))(20K) = 40,000J
4. The water will require more heat.

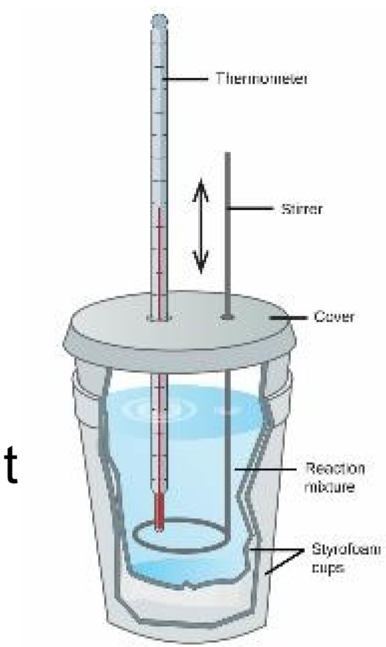
$c_{aluminum} \approx$ 900 J/(kg*K)
$c_{water} \approx$ 4,000 J/(kg*K)

Calorimetry: Measuring heat-energy transfer via temperature changes

- Suppose I want to measure how much heat-energy a chemical reaction dumps into a fluid. How do I do it?
- By measuring the temperature before and after the reaction, we get ΔT.
- If we measure the mass of our fluid and know the specific heat, then the heat energy is given by $Q = mc\Delta T$
- The energy "lost" by the chemical reaction is gained by the surrounding environment:
  - $Q_{lost} = Q_{gained}$



- A key detail is that the stuff you care about (the system), e.g. the chemical reaction stuff + the water in this picture, must be thermally isolated from the surrounding environment (here by coffee cups)



Sect 14.2

Two liters of water at 353K is added to 1.5-liters of water at 293K.
No energy is lost to the surroundings.
What is the final equilibrium temperature of the water?
Note, 1liter of water has a mass of 1kg.

(A) 293 K

(B) 323K

(C) 327K

(D) 353 K

1. $Q_{lost} = Q_{gained}$
2. $(mc\Delta T)_{2liters} = (mc\Delta T)_{1.5liters}$
3. $(2kg)(1000J/(kgK))(353K - T_{final}) = (1.5kg)(1000J/(kgK))(T_{final} - 293K)$
4. $2000J/K(353K - T_{final}) = (1500J/K)(T_{final} - 293K)$
5. $706{,}000J - (2000J/K)T_{final} = (1500J/K)T_{final} - 439{,}500J$
6. $1{,}145{,}500J = (3500J/K)T_{final}$
7. $T_{final} = (1{,}145{,}500J)(3500J/K) \approx 327K$

$c_{water} \approx 4{,}000\ J/(kg{*}K)$

You have two beakers of water, each with 1kg of water (c=4186J/(kgK)) at 293K. You drop one 353K block of 1kg of metal into each beaker, but one block is made of aluminum (c= 900J/(kgK)) and the other is made of copper (c= 386J/(kgK)). Once each beaker reaches thermal equilibrium with the block, which beaker of water has a higher temperature?

$c_{water} \approx 4{,}000$ J/(kg*K)

(A) beaker with aluminum

(B) beaker with copper

(C) both reach same equilibrium temperature

1. Aluminum has a larger specific heat capacity than copper.
2. This means it takes more energy to change the temperature of aluminum.
3. It also means that it donates more energy is deposited by a change in temperature of the aluminum block, relative to copper.

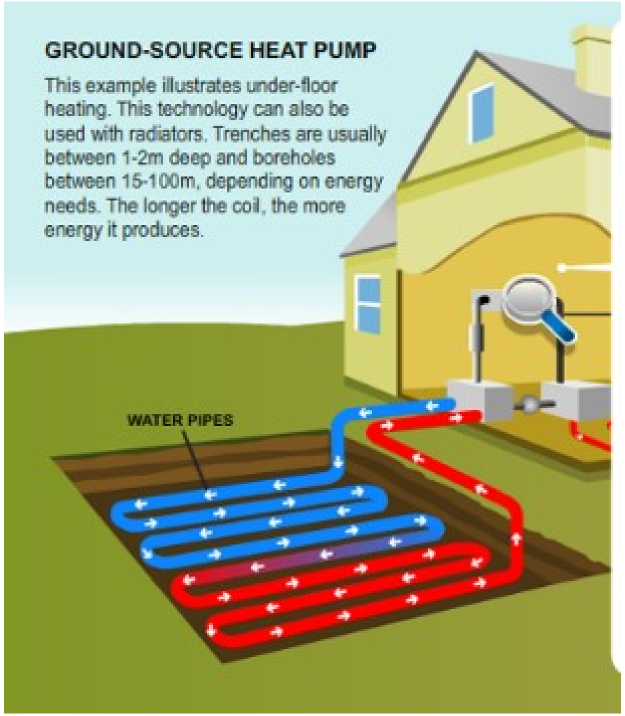
Math answer:

1. $Q_{lost} = Q_{gained}$
2. $(mc\Delta T)_{block} = (mc\Delta T)_{water}$
3. $m_{block}c_{block}(T_{block} - T_{final}) = m_{water}c_{water}(T_{final} - T_{water})$
4. $m_{block}c_{block}T_{block} - m_{block}c_{block}T_{final} = m_{water}c_{water}T_{final} - m_{water}c_{water}T_{water}$
5. $m_{block}c_{block}T_{block} - m_{water}c_{water}T_{water} = (m_{water}c_{water} + m_{block}c_{block})T_{final}$
6. $T_{final} = (m_{block}c_{block}T_{block} - m_{water}c_{water}T_{water})/(m_{water}c_{water} + m_{block}c_{block})$

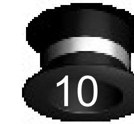
Thermal Energy Storage

- Large objects can be used as energy reservoirs by storing energy as heat.
- Excess energy can be stored as heat to be released later, or to smooth-out the power distribution from a different energy source.
  - E.g. store extra solar energy from the day or wind energy from a windy day to use later during the night.

- The earth itself is a large hot object (where the heat comes from radioactive decays inside the earth's core).
  This heat forms the basis of geothermal energy.



A 1kg block of aluminum (c=900J/(kgK)) has an initial temperature of 300K. The block is placed over an electric heater which provides 150W of power for 300 seconds.
After this heating episode, what is the temperature of the aluminum block?



(A) 50K

(B) 300K

(C) 350K

(D) 450K

1. $Q = mc\Delta T$
2. $\Delta T = Q/mc$
3. $Q = P*t = 150W*300s = 45{,}000J$
4. $\Delta T = (45{,}000J)/(1kg*900J/(kgK)) = 50K$
5. $T_{final} = T_{initial} + \Delta T = 300K + 50K = 350K.$

1W = 1J/s