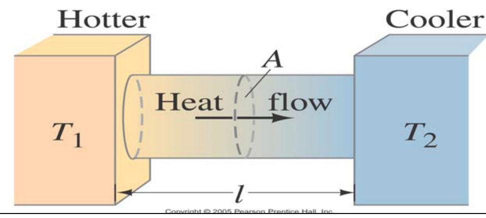
Heat Transfer Methods

- Conduction: Thermal kinetic energy passed from particle-to-particle along a length of material.
- Convection: Thermal energy carried by moving fluid.
- Radiation: Thermal energy carried by electromagnetic waves (light)

Conduction

- Heat conduction can be visualized as occurring through molecular collisions.
- Thermal kinetic energy is passed along as "hotter" particles collide with "colder" ones.



Conduction

- Conduction is heat flow by direct contact.
- Some materials are good thermal conductors (like the tile), others are insulators (like the wood).

Conduction

- Rate of heat transferred via conduction:

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

k = thermal conductivity (W/m K)
A = cross-sectional area
L = length
T = temperature
t = time elapsed

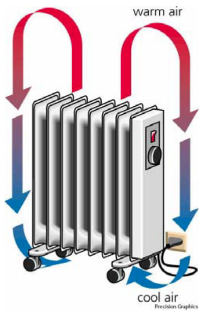
Example: Imagine standing on a cold wood floor vs. a carpeted floor. If you stand around for 5 minutes and the temperature in your foot drops by 30K, which foot did you lose more heat from? How much more?

Convection

- Convection is flow of fluid due to difference in temperatures, such as warm air rising.
- Fluid "carries" heat with it as it moves.
- "Natural" convection: Warm fluid will rise because it is less dense then cold fluid.

Convection

- Heat transfer in a fluid often occurs mostly by convection.
- Buoyancy causes warm air to rise, which carries thermal energy directly by its motion.



Fiberglass Insulation

- Air is a poor thermal conductor but easily transfers heat by convection.
- Fiberglass insulation is mostly air, with the fibers disrupting the convection flow.

Radiation

- How does energy get from the Sun to Earth?
- No atmosphere out in space, so it's can't be convection or conduction
- The energy is transferred through radiation; specifically, *electromagnetic radiation*

Radiation

- Infrared light can radiate away from an object even in a vacuum (no air = no convection).
- Heat flow:

$$Q/\Delta t = e\,\sigma\,AT^4$$

A = surface area

e = emissivity

σ = Stefan-Boltzmann constant

5.67×10^{-8} W/(m² K⁴) → $5.67 \times 10^{-8}\ W/(m^2 K^4)$

If you were trying to warm your hands with a bonfire, where would you place your hands to warm them up as quickly as possible?

A. To the left of the bonfire
B. To the right of the bonfire
C. Above the bonfire
D. Anywhere; the exact location doesn't matter

Conceptual Check:

Spend a few minutes discussing with a neighbor how you could cool a hot cup of coffee. Try to explain how the cooling would happen using the ideas we've learned about heat transfer.

Pressure in Gases

- Ideal gas law!

  $PV = Nk_BT$ (or $PV=nRT$)

- If we imagine a sealed container, then N is a constant (no gas can get in or out), and we can compare various states:

  $P_1V_1/T_1 = P_2V_2/T_2$

Kinetic Theory

- Pressure comes from collisions between pairs of individual particles, and from collisions between particles and their container.
- Assume that you have an ideal gas, and collisions are also ideal (no energy lost, only exchanged between particles)
- Allows us to relate microscopic (position & velocity of particles in a substance) to properties to macroscopic properties (pressure, temp in a substance)

Thermal Energy in a Gas

- Careful! Temperature and thermal energy are NOT the same thing, even though thermal energy depends on temperature.
- Temperature: KE_{avg}
- Thermal Energy: KE_{tot}

$$E_{th} = (3/2)\, Nk_BT$$

N = number of atoms
$k_B = 1.38 \times 10^{-23}$ J/K (Boltzmann's constant)
T = temperature in Kelvins

Two gases have the same thermal energy. One gas has twice as many atoms as the other. Which gas is at a higher temperature?

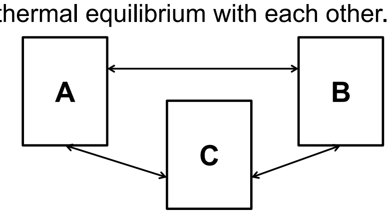
A. The gas with fewer atoms.
B. The gas with more atoms.
C. Neither; they are at the same temperature.

Two gases have the same thermal energy. One gas has double the temperature of the other. Which gas contains a larger number of atoms?

A. The gas with the lower temperature.
B. The gas with the higher temperature.
C. Neither; they contain the same number of atoms.

0^{th} Law of Thermodynamics

- Imagine three systems: A, B, and C
- If A and B are each in thermal equilibrium with C, then A and B must also be in thermal equilibrium with each other.



1st Law of Thermodynamics

When heat flows to (or from) a system, the system gains (or loses) an amount of energy equal to the amount of heat transferred.

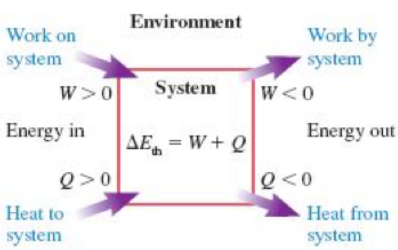
Caution: Remember that numerically,
$\Delta Q \neq \Delta Temp$!

1st Law of Thermodynamics

$$\Delta E_{th} = \Delta Q + \text{work}$$

- This is the thermal version of conservation of energy!
- You can never get more energy out of a closed system than you originally put in

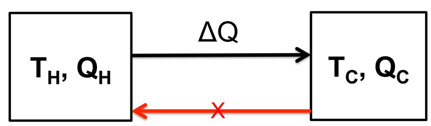
Work and Q can be positive or negative numbers



2nd Law of Thermodynamics

Heat **<u>of itself</u>** never flows from a cold object to a hot object.

And, you can harness some but not all of that heat for useful work: $W_{out} = Q_H - Q_C$ and Q_C cannot be zero.



Efficiency Revisited: Heat Engines

e = Energy out/ Energy in

$e = W_{out} / Q_H$

$e_{max} = 1 - (T_C / T_H) \geq W_{out} / Q_H$

This is not a technological limit, but a real physical limit to the efficiency of a heat engine. Usually, the real efficiency isn't even as high as the theoretical efficiency!

Heat Engine Example

- T_H = 500K, T_C = 300K, Q_H = 250J and e = 0.25
- What is the amount of useful work done by the system?
- How much heat is exhausted into the cool reservoir?
- Does the heat engine obey the 2nd law of thermodynamics (is $e \leq e_{max}$)?

Heat Engines vs. Heat Pumps

- We can harness heat flowing from a high-temperature object to a low-temperature object to do work
- We can also do the reverse: do work on a system to force heat to flow the “wrong” direction.
- Air conditioners & refrigerators (depending on what you count as the desired output).

Efficiency Revisited: Refrigerators

efficiency = Energy out/ Energy in

$COP = Q_C / W_{in}$

$COP_{max} = T_C /(T_H - T_C) \geq Q_C / W_{in}$

Refrigerator Example

- We would like our refrigerator to stay at a temperature of at least 30F inside even on a very hot day (110F outside). In order to do so, we must move 300J of heat from the interior of the fridge to the exterior.
- T_H = 315K, T_C = 270K
- If the fridge has a COP of 4.5, does that satisfy the 2nd law of thermo? How much work do we need?

Entropy: Order vs. Disorder

In natural processes, high-quality energy tends to transform into lower-quality energy – order tends toward disorder.

So what in the world do high-quality and low-quality energy mean??

Entropy

- For a reversible process: $Q_C/T_C = Q_H/T_H$
- Define quantity of entropy: $\Delta S = Q/T$

- What if the process is NOT reversible (which is true of **any** real process)? No heat transfer is 100% efficient, so we must be dumping extra heat into the cold reservoir! $Q_C/T_C > Q_H/T_H$

Entropy always increases in closed systems

- Always look at where the energy comes from
- Remember that processes are very rarely isolated in any physical process
  - Will a box lift itself onto a shelf spontaneously?
  - Will the energy in your warm hands dissipate into the air spontaneously?

The "Heat Death" of the Universe

- Stars are producing energy (via fusion… more on that in Phys 121), and it radiates out in space.
- Stars have finite (although long) lifetimes; eventually they'll stop shining!
- What happens when no more stars can form?

Third Law of Thermodynamics

- You can never get to absolute zero
- Consider the second law: no process is 100% efficient
- "You can't get there from here" and taking an infinite number of steps

Thermodynamics Summary:

"You can't win, you can't break even, and you can't get out of the game."