Thermodynamics

Temperature, Heat, Work

Heat Engines

Introduction

- In mechanics we deal with quantities such as mass, position, velocity, acceleration, energy, momentum, etc.
- Question: What happens to the energy of a ball when we drop it on the floor?
- Answer: It goes into heat energy.
- Question: What is heat energy?

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The answer is a bit longer.

- In *Thermodynamics* we deal with quantities which describe our system, usually (but not always) a gas.
- Volume, Temperature, Pressure, Heat Energy, Work.

- We all know about Volume.
- Pressure:

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Example

- 120 lb woman putting all her weight on $2in^2$ of heals.
- Pressure = 120 $lb/2in^2$ = 60 lb/in^2.
- Is that a lot?
- Comparison: 1 atm = 14.7 lb/in^2. Thus of heals is approximately 4 atm.
- This is the pressure you would feel at a depth of approximately 133 ft of water.

Temperature and Heat

- Everyone has a qualitative understanding of temperature, but it is not very exact.
- Question: Why can you put your hand in a 400° F oven and not get instantly burned, but if you touch the metal rack, you do?
- Answer: Even though the air and the rack are at the same temperature, they have very different energy

Construction of a Temperature Scale

- Choose fixed point temperatures that are easy to reconstruct in any lab, e.g. freezing point of water, boiling point of water, or anything else you can think of.
- Fahrenheit: Original idea:

0°F	Freezing point of Salt/ice
100°F	Body Temperature

Using this ice melts at 32°F and water boils at 212°F (Not overly convenient) Note: 180°F between boiling an freezing.

- Celsius (Centigrade) Scale:

  $0^\circ C$ Ice Melts

  $100^\circ C$ Water Boils

Note a change of $1^\circ C$ = a change of $1.8^\circ F$.

Conversion between Fahrenheit and Celsius

If we know Celsius and want Fahrenheit

$$F = \frac{9}{5}C + 32$$

If we know Fahrenheit and want Celsius

$$C = \frac{5}{9}\left(F - 32\right)$$

Absolute or Kelvin Scale

- The lowest possible temperature on the Celsius Scale is -273°C.
- The Kelvin Scale just takes this value and calls it 0K, or absolute zero.
- Note: the “size” of 1K is the same as 1°C.
- To convert from C to K just add 273.

$$K=C+273$$

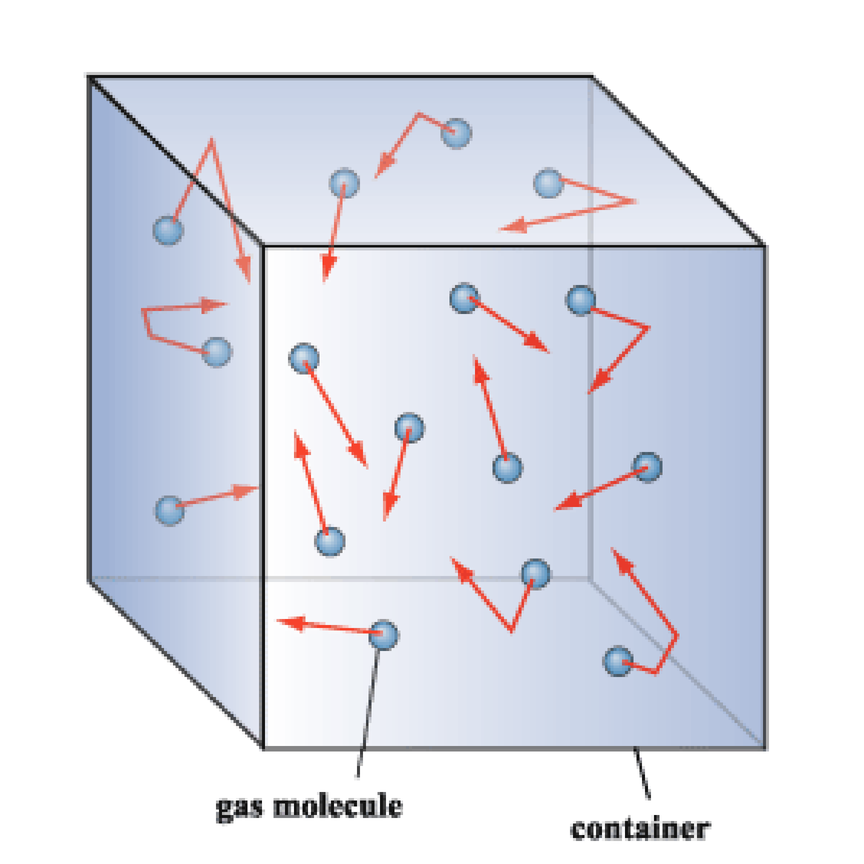
When do you use which scale.

- Never use Fahrenheit, except for the weather.
- You can always use Kelvin and you must use Kelvin when doing absolute temperature measurements.
- You can use either Kelvin or Celsius when measuring differences in temperature.

Heat

- Heat is the random motion of the particles in the gas, i.e. a “degraded” from of kinetic energy.

- Nice web simulation
- gas simulation



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- The higher the temperature, the faster the particles (atoms/molecules) are moving, i.e. more Kinetic Energy.
- We will take heat to mean the thermal energy in a body OR the thermal energy transferred into/out of a body

Specific Heat

- Observational Fact: It is easy to change the temperature of some things (e.g. air) and hard to change the temperature of others (e.g. water)
- The amount of heat (Q) added into a body of mass m to change its temperature an amount ΔT is given by

$$Q=m\,C\,\Delta T$$

- C is called the specific heat and depends on the material and the units used.
- Note: since we are looking at changes in temperature, either Kelvin or Celsius will do.

Units of Heat

- Heat is a form of energy so we can always use Joules.
- More common in thermodynamics is the calorie: By definition 1 calorie is the amount of heat required to change the temperature of 1 gram of water 1°C.
- 1 Cal = 1 food calorie = 1000 cal.

- The English unit of heat is the Btu (British Thermal Unit.) It is the amount of heat required to change the temperature of 1 lb of water 1°F.

- Conversions:

$$1 \text{ cal} = 4.186 \text{ J}$$

$$1 \text{Btu} = 252 \text{ cal}$$

Units of Specific Heat

$$C = \frac{Q}{m\Delta T} = \left(\frac{cal}{g\,^{o}C}\right) = \left(\frac{J}{kg\,^{o}C}\right)$$

Note that by definition, the specific heat of water is 1 cal/g°C.

Material	J/kg°C	cal/g°C
Water	4186	1
Ice	2090	0.50
Steam	2010	0.48
Silver	234	0.056
Aluminum	900	0.215
Copper	387	0.0924
Gold	129	0.0308
Iron	448	0.107
Lead	128	0.0305
Brass	380	0.092
Glass	837	0.200
Wood	1700	0.41
Ethyl Alcohol	2400	0.58
Beryllium	1830	0.436

Water has a specific heat of 1 cal/gmK and iron has a specific heat of 0.107 cal/gmK. If we add the same amount of heat to equal masses of iron and water, which will have the larger change in temperature?

1. The iron.
2. They will have equal changes since the same amount of heat is added to each.
3. The Water.
4. None of the above.

Example Calculation

- Compare the amount of heat energy required to raise the temperature of 1 kg of water and 1 kg of iron 20 °C?

$$Q = mC\Delta T$$

For Water

$$Q = (1000\,g)(1\,cal/g\,^{o}C)(20^{o}\,C) = 20,000\,cal$$

For Iron

$$Q = (1000\,g)(0.107\,cal/g\,^{o}C)(20^{o}\,C) = 2140\,cal$$

Heat Transfer Mechanisms

1. Conduction: (solids--mostly) Heat transfer without mass transfer.
2. Convection: (liquids/gas) Heat transfer with mass transfer.
3. Radiation: Takes place even in a vacuum.

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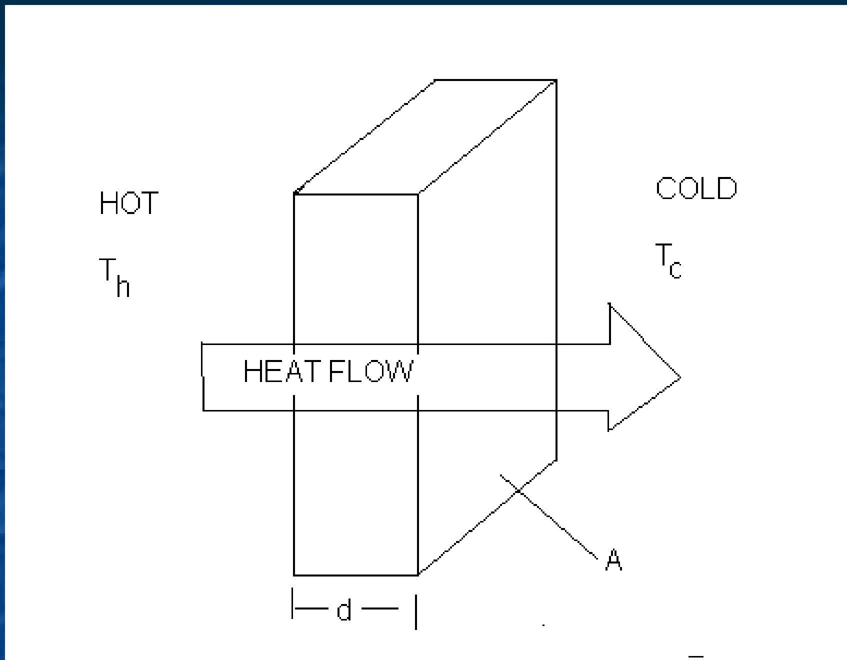


Conduction

Rate of Heat Flow

Thermal Conductivity

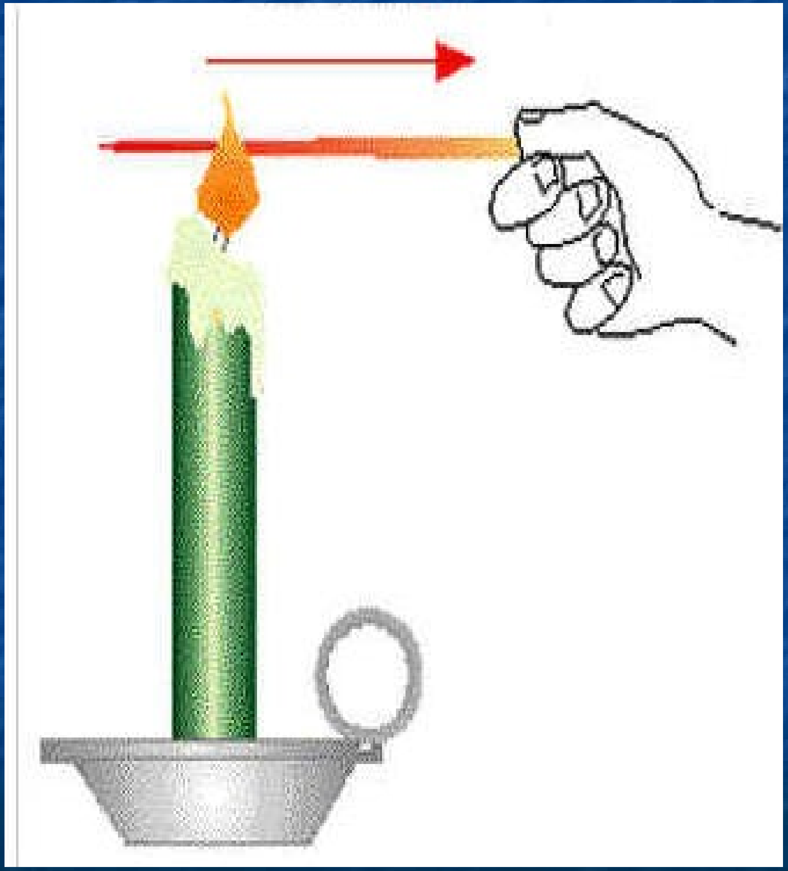
Contact Area

Temperature Difference

Thermal Conductivity of Common Materials (at 25° C)

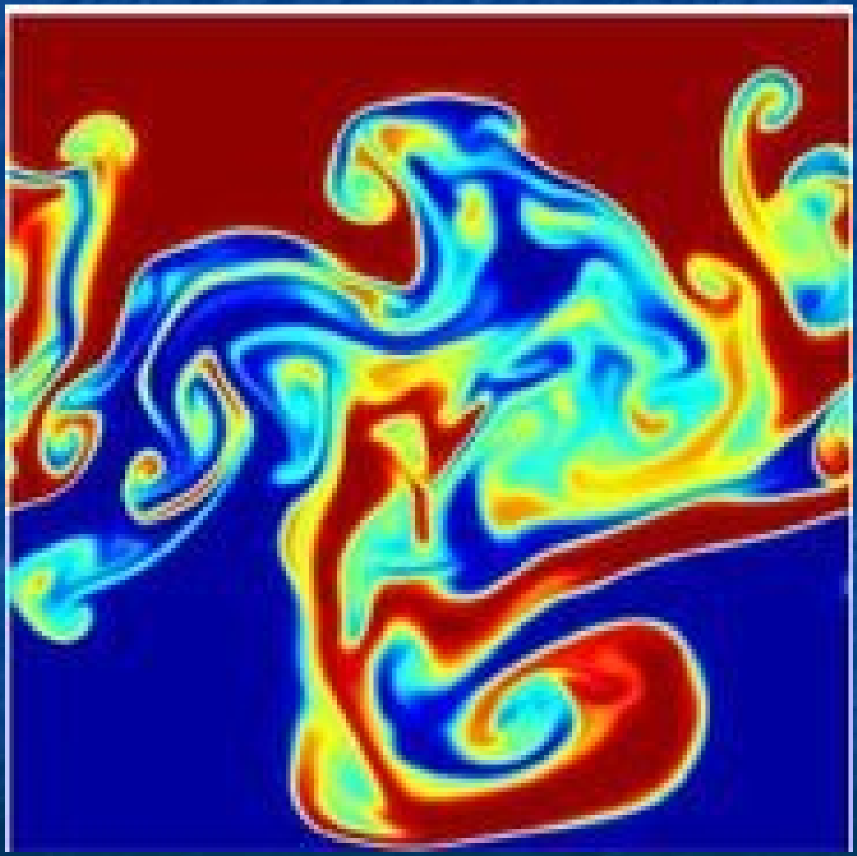
Material	Conductivity (Watts/meter-°C)
Acrylic	0.200
Air	0.024
Aluminum	250.000
Copper	401.000
Carbon Steel	54.000
Concrete	1.050
Glass	1.050
Gold	310.000
Nickel	91.000
Paper	0.050
PTFE (Teflon®)	0.250
PVC	0.190
Silver	429.000
Steel	46.000
Water	0.580
Wood	0.130

Example

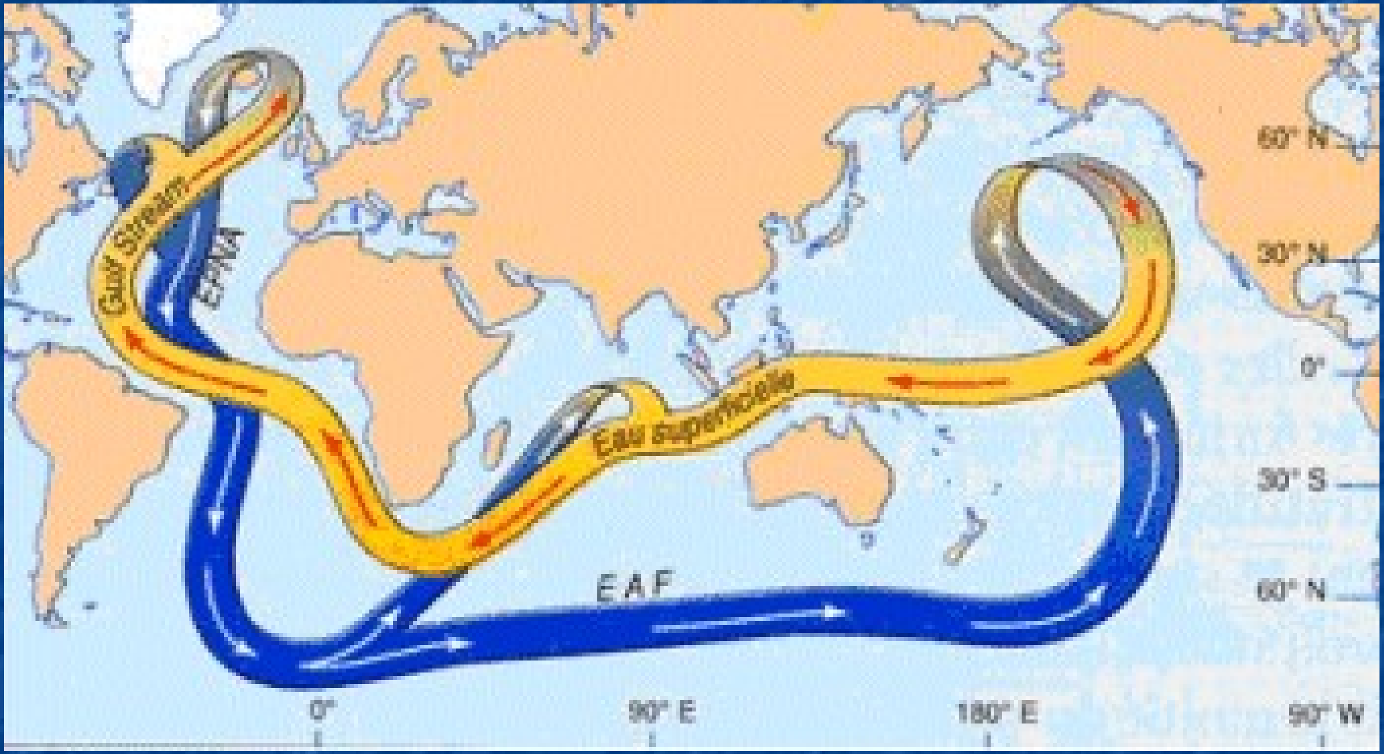


Convection

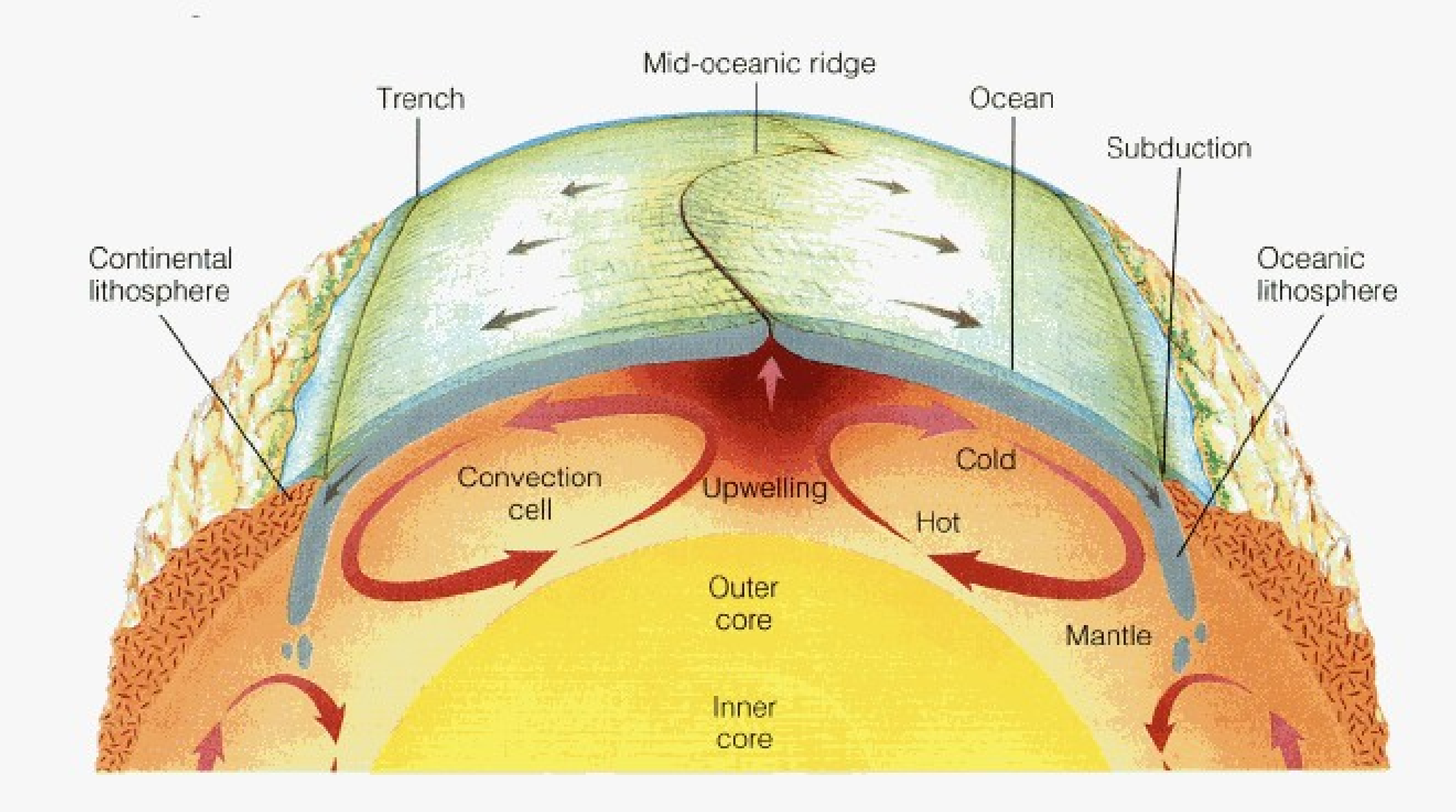
- Typically very complicated.
- Very efficient way to transfer energy.
- Vortex formation is very common feature.
- liquid convection
- vortex formation
- Sunspot
- solar simulation



Convection Examples



- Ocean Currents



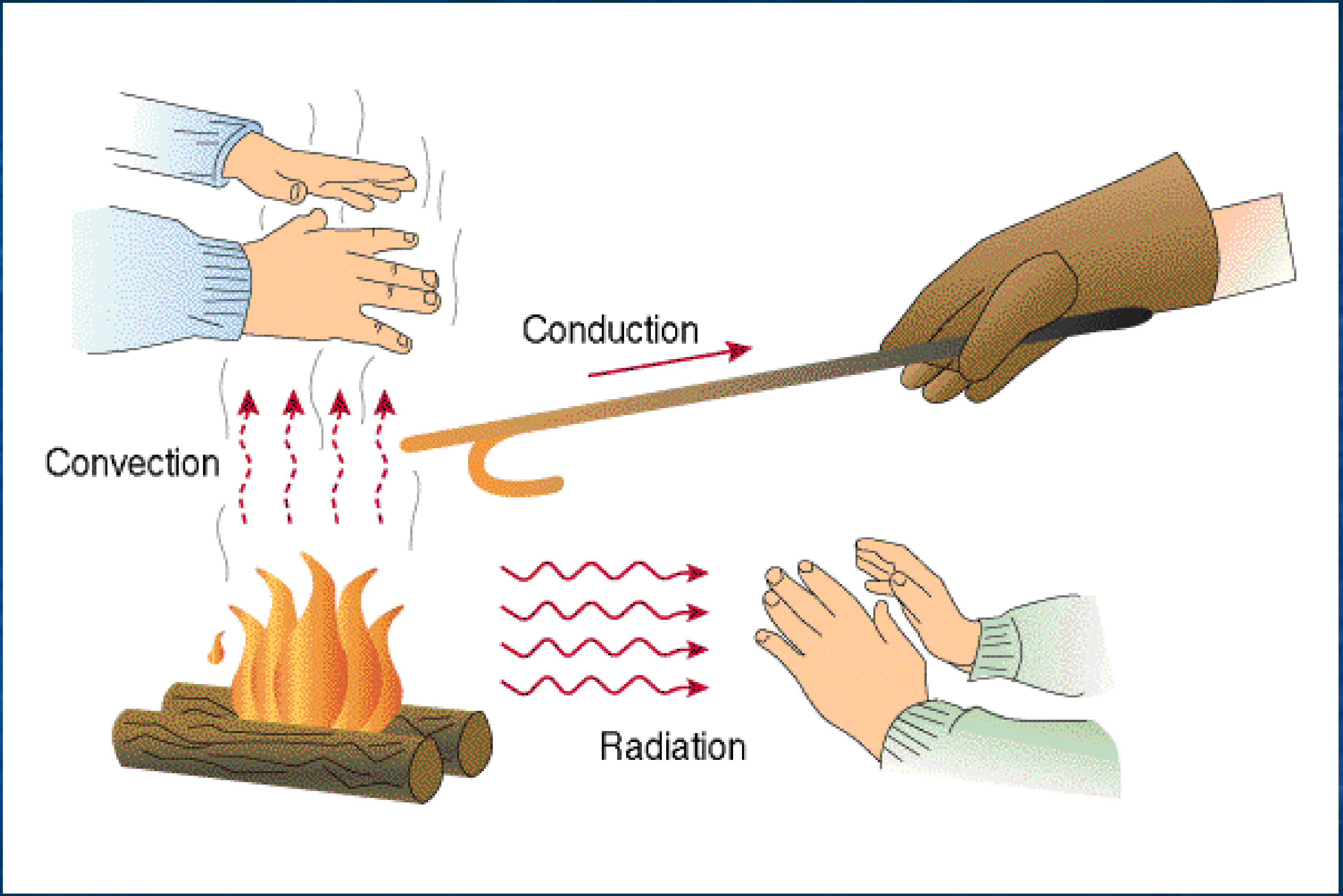
- Plate tectonics

Radiation

- Everything that has a temperature radiates energy.
- Method that energy from sun reaches the earth.

$$P = \frac{Q}{t} = \sigma e A T^4 = (const) T^4$$

- Note: if we double the temperature, the power radiated goes up by $2^4 = 16$.
- If we triple the temperature, the radiated power goes up by $3^4 = 81$.
- A lot more about radiation when we get to light.

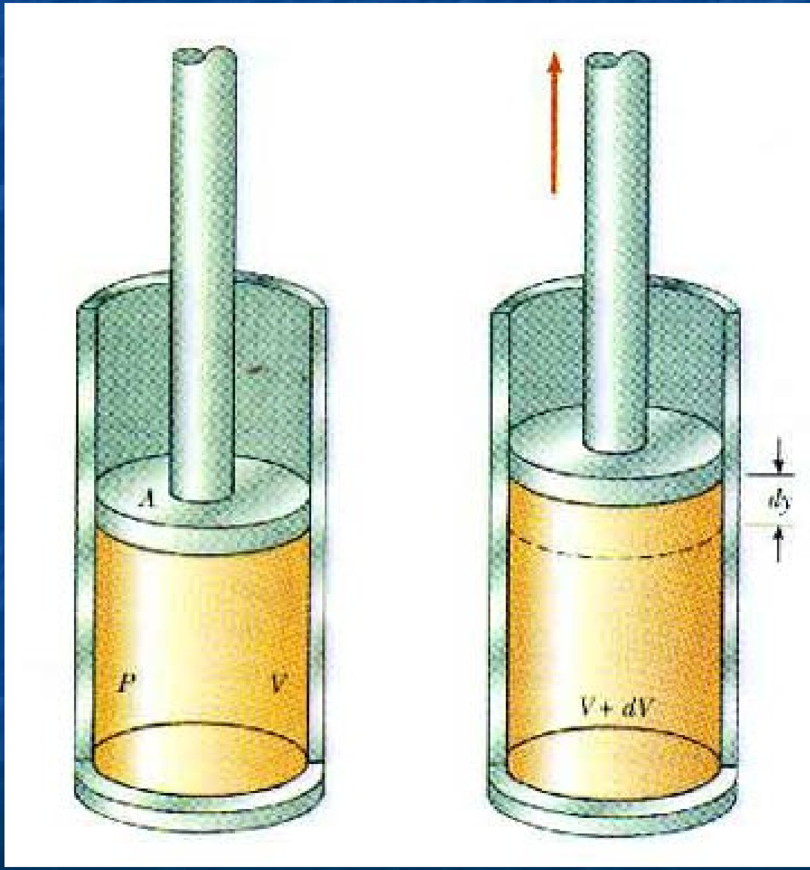

Conduction
Convection
Radiation

Work Done by a Gas

- Work= (Force)x(distance)

  $=F\Delta y$
- Force= (Pressure)x(Area)
- $W=P(A\Delta y)$

  $=P\Delta V$



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First Law of Thermodynamics Conservation of energy

- When heat is added into a system it can either 1) change the internal energy of the system (i.e. make it hotter) or 2) go into doing work.

$$Q=W+\Delta U.$$

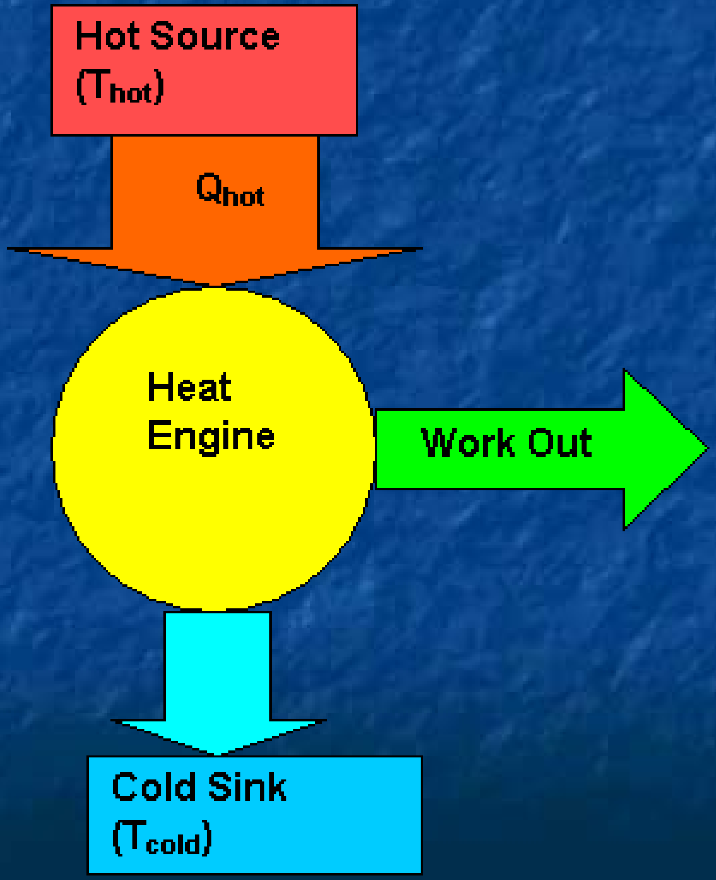
Note: For our purposes, Internal Energy is the part of the energy that depends on Temperature.

Heat Engines

- If we can create an “engine” that operates in a cycle, we return to our starting point each time and therefore have the same internal energy. Thus, for a complete cycle

$$Q = W$$

Model Heat Engine



- $Q_{hot} = W + Q_{cold}$

or

- $Q_{hot} - Q_{cold} = W$

(what goes in must come out)

Efficiency

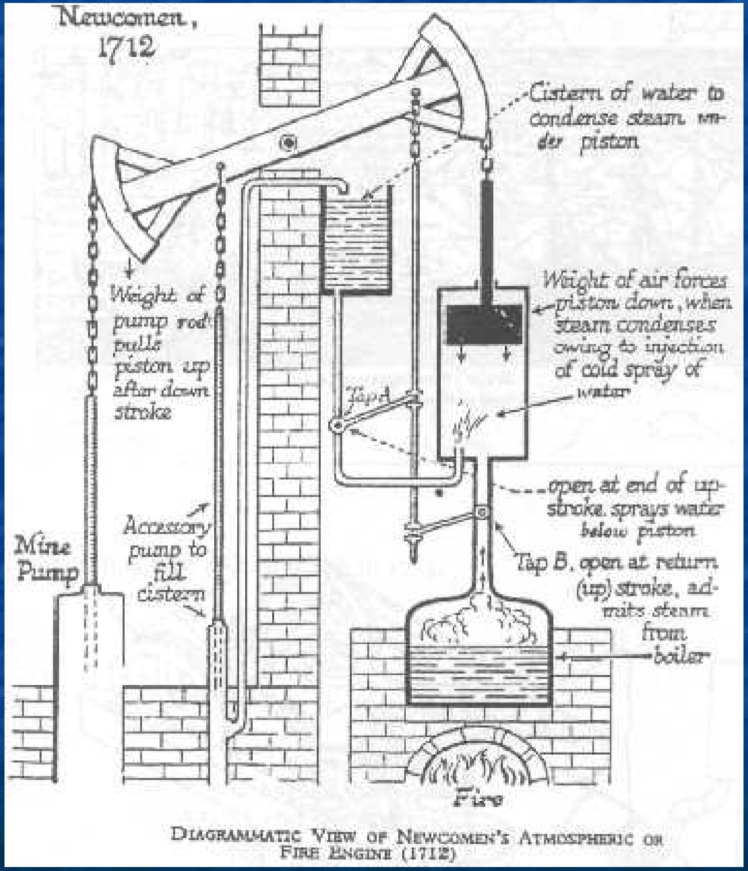
- We want to write an expression that describes how well our heat engine works.
- Q_{hot}=energy that you pay for.
- W=work done (what you want.)
- Q_{cold}= Waste energy (money).

Efficiency = e = W/Q_{hot}

- If we had a perfect engine, all of the input heat would be converted into work and the efficiency would be 1.
- The worst possible engine is one that does no work and the efficiency would be zero.
- Real engines are between 0 and 1

$$e = \frac{W}{Q_{hot}} = \frac{Q_{hot} - Q_{cold}}{Q_{hot}} = 1 - \frac{Q_{cold}}{Q_{hot}}$$

Newcomen Engine
(First real steam engine)



$e=0.005$

Example Calculation

- In every cycle, a heat engine absorbs 1000 J from a hot reservoir at 600K, does 400 J of work and expels 600 J into a cold reservoir at 300K. Calculate the efficiency of the engine.
- e= 400J/1000J=0.4
- This is actually a pretty good engine.

Second Law of Thermodynamics (What can actually happen)

- Heat does not voluntarily flow from cold to hot.

OR

- All heat engines have $e<1$. (Not all heat can be converted into work.)

Carnot Engine

- The very best theoretically possible heat engine is the Carnot engine.
- The efficiency of a Carnot engine depends on the temperature of the hot and cold reservoirs.

$$e_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

Note: The temperatures must be measured in Kelvins!!!

Example Calculation Part II

- In every cycle, a heat engine absorbs 1000 J from a hot reservoir at 600K, does 400 J of work and expels 600 J into a cold reservoir at 300 K. Calculate the efficiency of the best possible engine.
- $e = 1 - 300/600 = 0.5$
- Recall that the actual engine has $e=0.4$.