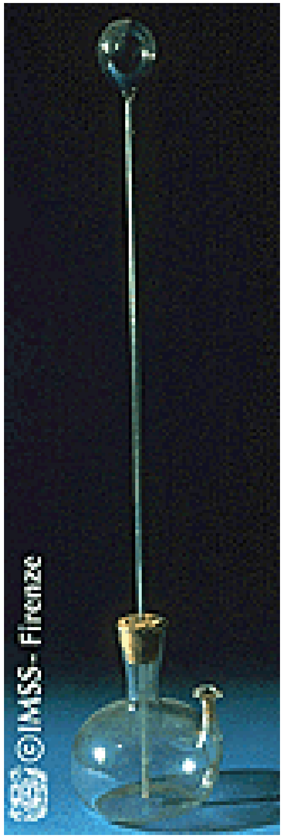
Chapter 10

Temperature and Heat





Thermodynamics deals with

1. Temperature.
2. The transfer and transformation of energy.
3. The relationship between macroscopic properties and microscopic dynamics.

Temperature and Heat

- On a cold morning does a tile floor feel as warm as a carpeted floor in the same room? They are the same temperature.
  - Temperature is not the same as our perception of hot and cold.
- The Physics definition of heat has a precise meaning which is not the same as temperature or our sense of hot and cold.

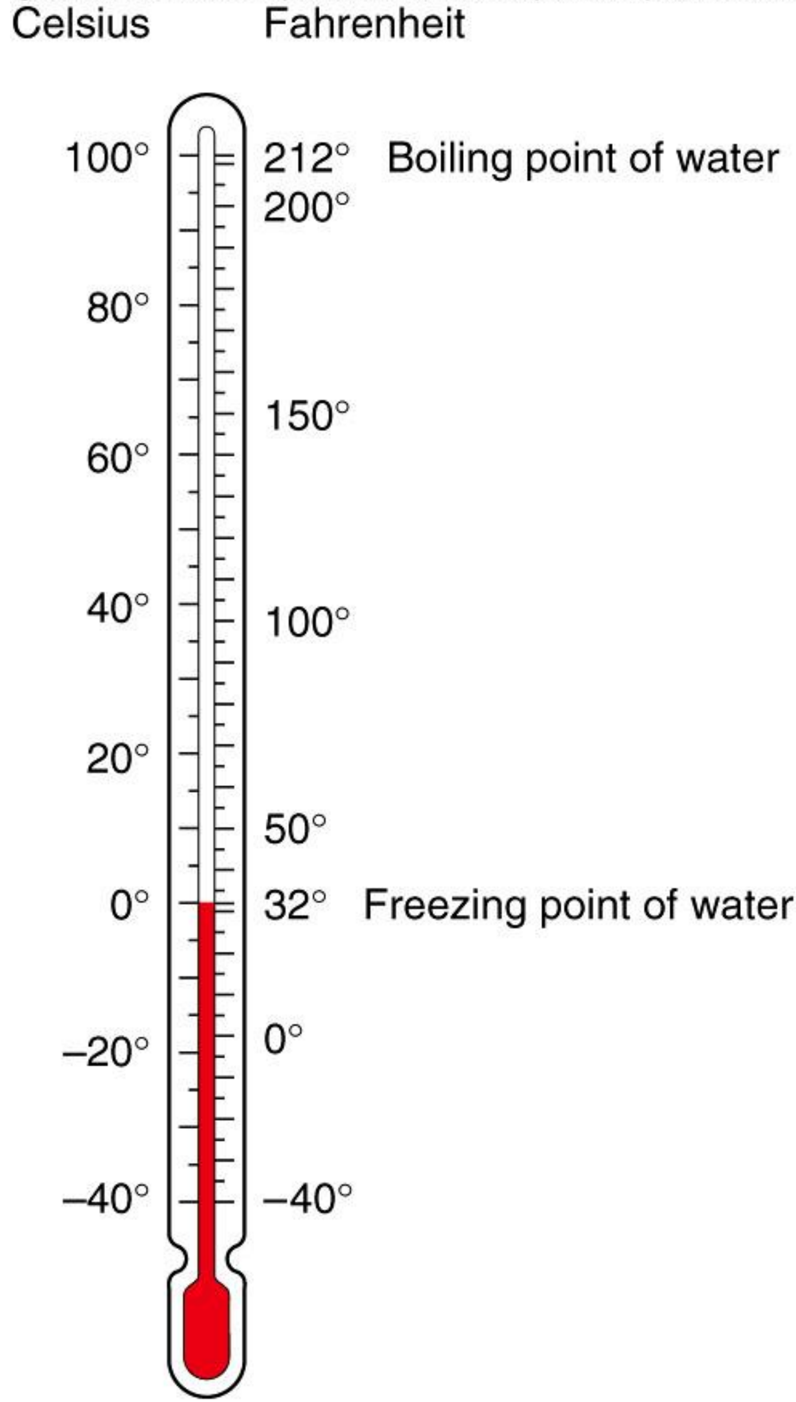
Temperature and Thermal Equilibrium

- Temperature is a property of an object
- If two objects are in contact with one another long enough, they will eventually have the same temperature.
- When they have *the same temperature* we say they are in *thermal equilibrium*.
- **The zeroth law of thermodynamics**
  - If two objects are each in thermal equilibrium with a third object, they are in thermal equilibrium with each other. (i.e. they have the same temperature.)

- The SI scale for temperature is Celsius, T_C, (named after Anders Celsius)
- In the U.S. we use the Fahrenheit scale , T_F, (named after Gabriel Fahrenheit)
- One Celsius degree is larger than one Fahrenheit degree: the ratio of Fahrenheit degrees to Celsius degrees is 180/100, or 9/5.
- They are equal at -40°.

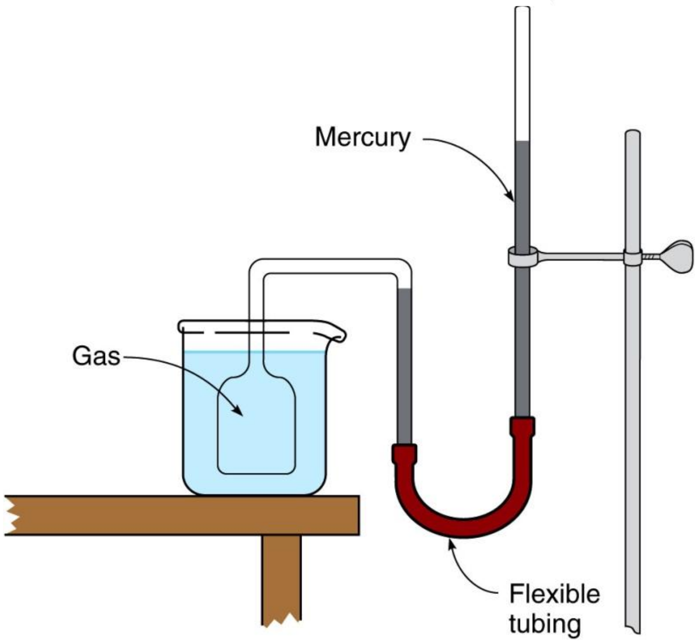
$$T_C = \frac{5}{9}\left(T_F - 32\right)$$

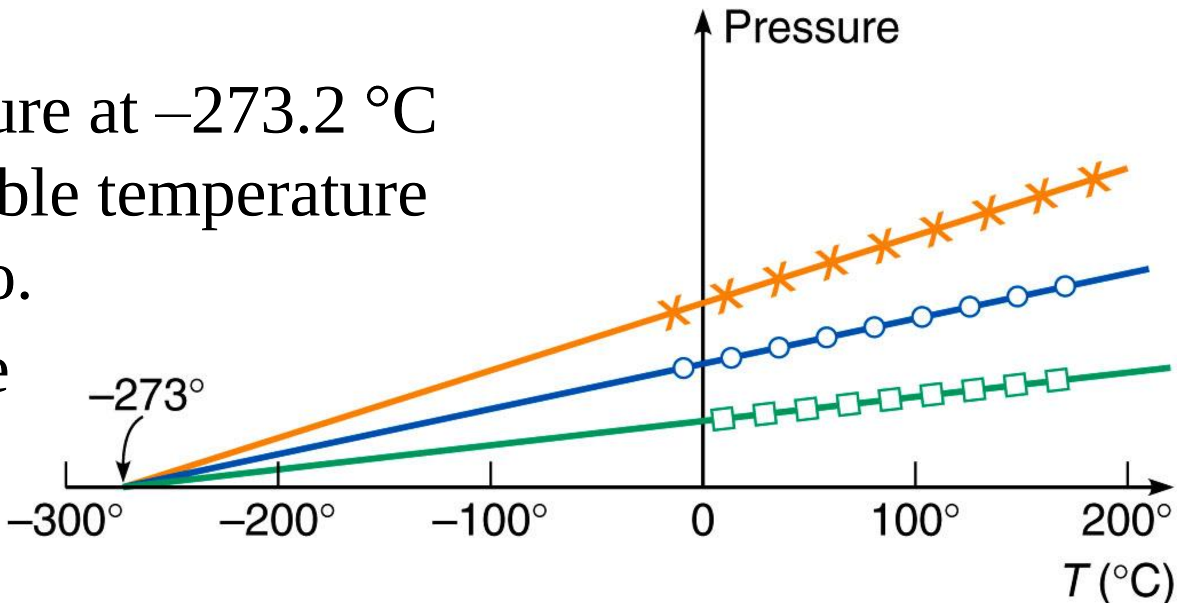
$$T_F = \frac{9}{5}T_C + 32$$



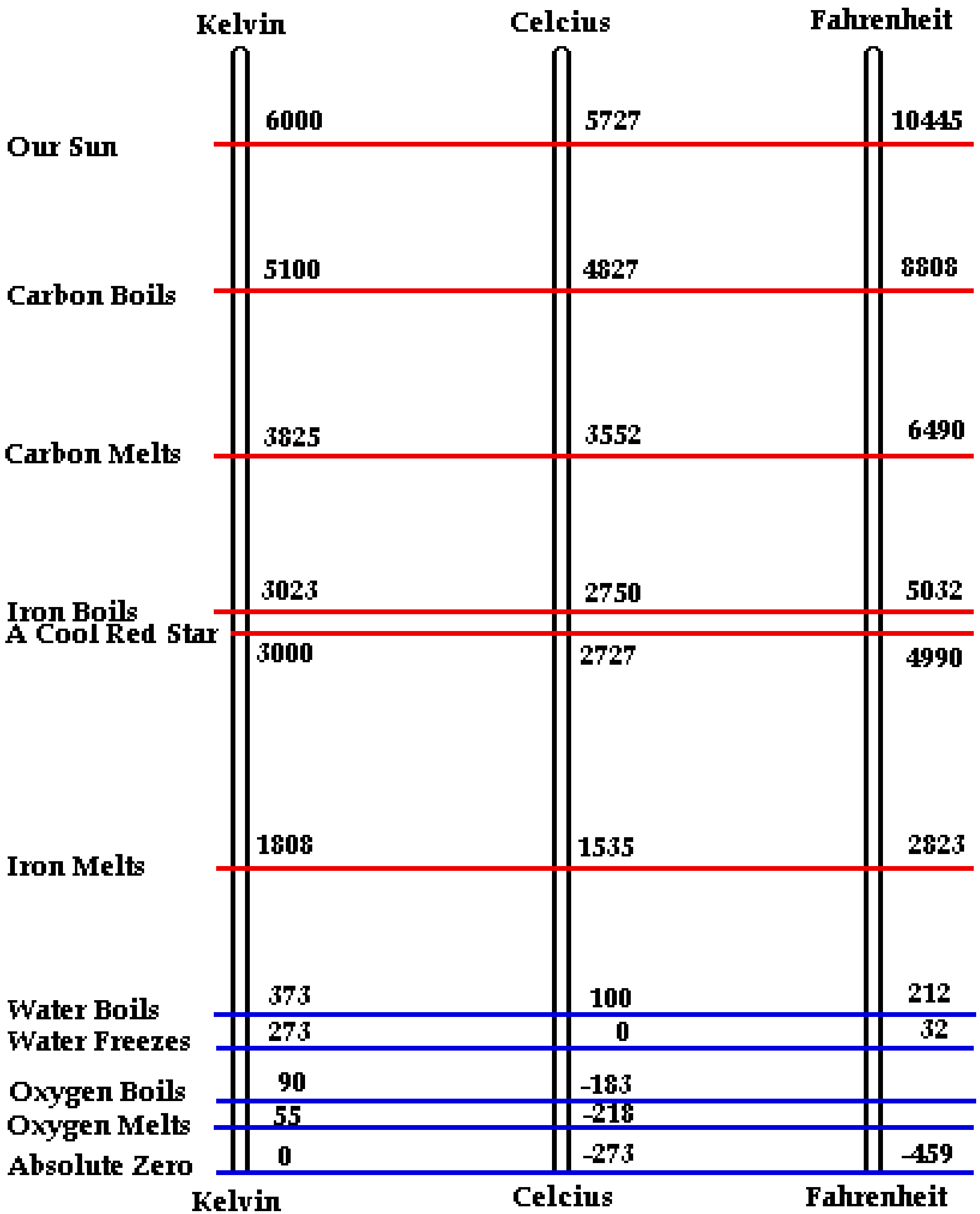
Absolute Zero: The lowest possible temperature

- If the volume of a gas is kept constant while the temperature is decreased, the pressure will decrease.
- A constant-volume gas thermometer uses this to measure temperature.
- The difference in height of the two mercury columns is proportional to the pressure, which is also proportional to temperature
- Any gas has zero pressure at –273.2 °C
- This is the lowest possible temperature in nature: Absolute zero.
- The Kelvin temperature scale sets this value to be 0 K.





Common Temperature Scales



$$T_C = (5/9)(T_F - 32)$$
$$T_F = (9/5)T_C + 32$$
$$T = T_C + 273.2\ \text{K}$$

- The size of 1 ºC is the same as 1 K. The only difference is an offset by 273.2
- Nothing can ever get colder than (or even as cold as) absolute zero (0 K)

Heat

- Recall that the definition of "work" was the transfer of energy into or out of a system due to a force acting over some distance.
- The definition of "heat" (*Q*) is the transfer of energy into or out of a system due to a difference in temperature.
- Heat is measured in energy units.
  – SI: Joules
- We say heat flows from a hot to a cold object. A more accurate statement would be that energy is transferred from an object with a higher temperature to one with a lower temperature (never spontaneously the other way around.)

What can happen when heat is added to a system?

There are three possibilities

1) A temperature increase

   The object gets hotter

2) A phase change

   A solid changes to a liquid, or a liquid changes to a gas

3) An isothermal expansion

   A gas expands at a constant temperature

Specific Heat Capacity

- Specific heat capacity (c) is a property of a material
- It is a measure of how much heat must flow into or out of a system in order to change its temperature by a certain amount.

$$\boxed{Q = mc\Delta T}$$

Q = quantity of heat
m = mass of object
c = specific heat capacity of object
ΔT = change in temperature ($T_f - T_i$)

- Q is positive when the temperature increases and heat flows into the system.
- Q is negative when the temperature decreases and heat flows into the system.

Specific heat capacity is often given in units of cal/g·ºC which is not an SI unit.

- 1 cal is approximately the amount of energy needed to raise 1 g of water by 1° C
- 1 Btu is approximately the amount of energy needed to raise 1 pound of water by 1° F

To change units:

1 cal = 4.186 J

1 kcal = 1 Calorie (this is a food "calorie")

1 cal/g·C° = 1 Btu/lb·F° = 4186 J/kg·K

Interactive Question

Given that the same amount of heat will affect the following objects in the following ways. Which object has the greatest specific heat capacity?

A) Raises the temperature of 3 g of substance 1 by 10 K
B) Raises the temperature of 4 g of substance 2 by 4 K
C) Raises the temperature of 6 g of substance 3 by 15 K
D) Raises the temperature of 8 g of substance 4 by 6 K
E) Raises the temperature of 10 g of substance 5 by 10 K

Interactive Question

Two objects of different temperatures are brought together. Eventually the objects reach thermal equilibrium. Which of the following statements is true once they have reached thermal equilibrium?

A) They are at the same temperature.
B) The absolute value of the temperature change of each object was the same.
C) Both objects have the same specific heat.
D) More than one of the above is true.

Problem: How much heat does it take to make a cup of coffee? Assume that for your 12 oz. cup of coffee the water starts at 20 ^{o}C and reaches near boiling at 95 ^{o}C.

What can happen when heat is added to a system?

There are three possibilities

1) A temperature increase

   $Q = mc\Delta T$

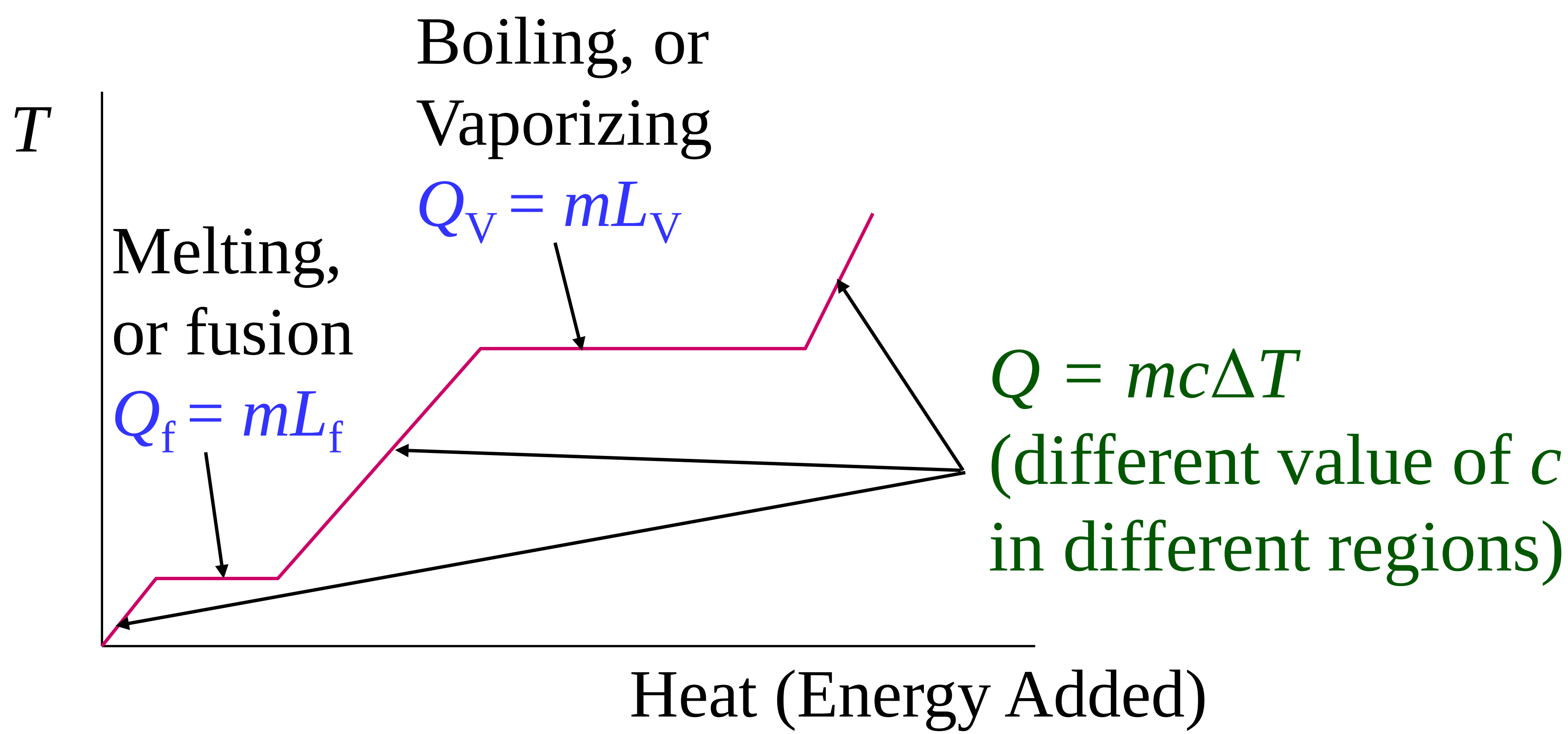
2) A phase change

   A solid changes to a liquid, or a liquid changes to a gas

3) An isothermal expansion

   A gas expands at a constant temperature

Phase Change due to Heat:



$Q_f = mL_f$

$Q_V = mL_V$

L_f: "latent heat of fusion"

L_V: "latent heat of vaporization."

m: mass

Interactive Question

An amount of heat is added to ice, raising its temperature from -10 C to -5 C. A larger amount of heat is added to the same mass of liquid water, raising its temperature from15 C to 20 C. From these results, we conclude that

A) overcoming the latent heat of fusion of ice requires an input of energy
B) the latent heat of fusion of ice delivers some energy to the system
C) the specific heat of ice is less than that of water
D) the specific heat of ice is greater than that of water

Problem: You take a 110 gram ice cube out of the freezer and it has a temperature of –18 ^{o}C? How much heat, in calories, does it take to completely melt the ice?

Interactive Question

Which is more likely to cause more damage to skin, a burn caused by water at 100 ^{o}C or a burn caused by steam at 100 ^{o}C?

A) The burn caused by water.
B) The burn caused by steam.
C) There is no difference.

What can happen when heat is added to a system?

There are three possibilities

1) A temperature increase

   $Q = mc\Delta T$

2) A phase change

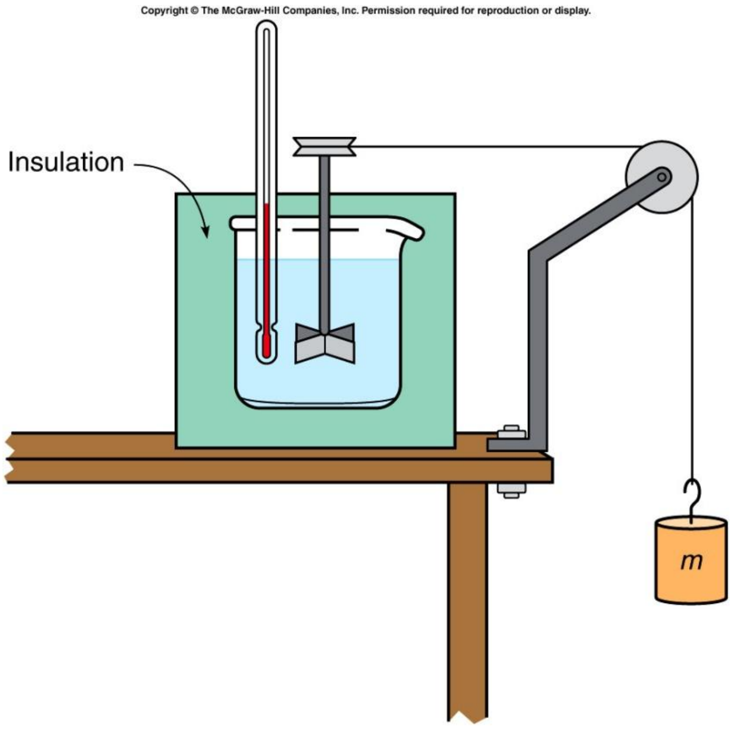
   $Q = mL$

3) An isothermal expansion

   A gas expands at a constant temperature

Joule’s Experiment

- Rumford noticed that cannon barrels became hot during drilling.
- Joule performed a series of experiments showing that mechanical work could raise the temperature of a system.
  - In one experiment, a falling object turned a paddle in an insulated beaker of water, producing an increase in temperature.
- The end result was a realization that both work and heat are energy transfers into or out of a system.



Conservation of Energy and Thermodynamics

In Chapter 6 we wrote the conservation of energy as

$$W_{\text{on}} = \Delta\text{PE} + \Delta\text{KE}$$

Environment

Energy transfer

Work = W_{on}

System

- Motional energy
  = kinetic energy = KE
- Stored energy
  = potential energy = PE
- Other kinds of energy we won't discuss

- Add a new type of energy to the system, internal energy (U)
- Add another way to transfer energy into the system, Heat (Q)
- Change the definition of work from work done *on* the system to work done *by* the system ($W = -W_{\text{on}}$)

The First Law of Thermodynamics

$$W_{\text{on}} = \Delta\text{PE} + \Delta\text{KE}$$

$$-W + Q = \Delta\text{PE} + \Delta\text{KE} + \Delta U$$

When $\Delta\text{PE} = \Delta\text{KE} = 0$

$$\boxed{Q = W + \Delta U}$$

This is the first law of thermodynamics. It is really just another way to write the conservation of energy in the special circumstance when there is no change in macroscopic potential energy or kinetic energy. The work in this equation is the work done *by* the system. The internal energy (U) is the microscopic kinetic and potential energy of the atoms and molecules in the system.

Interactive Question

The first law of thermodynamics states that the increase in internal energy of a system is equal to

A) the amount of heat added to the system minus the amount of work done on the system

B) the amount of heat added to the system plus the amount of work done on the system

C) the amount of heat added to the system minus the amount of work done by the system

D) the amount of heat added to the system minus the amount of work done on the system

Problem: A 50 g lead bullet is moving at 250 m/s when it strikes a wall and stops. If all the energy of the bullet is converted to heat which is absorbed by the bullet, by how much does its temperature change?

Problem: In order to melt ice, you put a pan on the stove and heat it while stirring the ice. If the ice is initially at 0 ºC, you do 400 J of work by stirring, and the stove adds 500 cal of heat, how much ice is melted?

Heat and Internal Energy

The previous problem illustrates an important principle. We have discussed what can happen when heat is added to a system:

- A temperature increase: $Q = mc\Delta T$
- A phase change: $Q = mL$

These are true when no work is done on the system.

When work is done on the system, both the work and the heat change the internal energy: $\Delta U = Q - W$

This total change in internal energy can change the phase or temperature so we can substitute ΔU for Q:

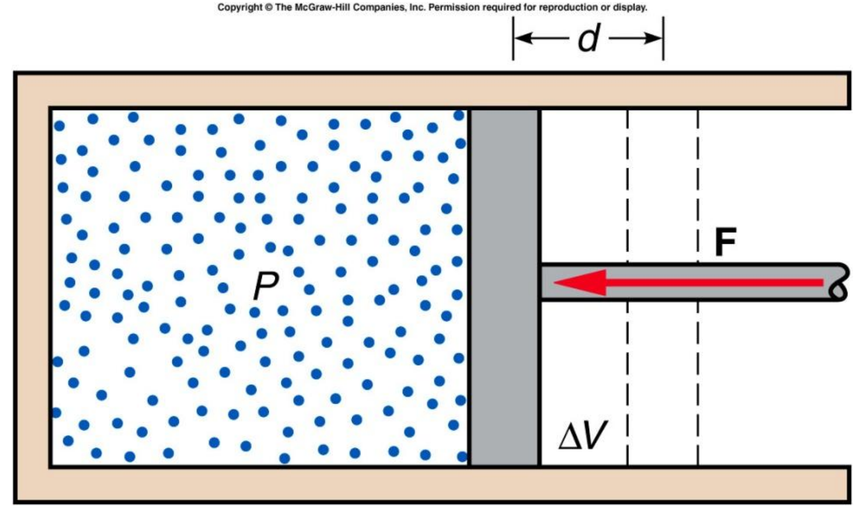
- A temperature increase: $\Delta U = mc\Delta T$
- A phase change: $\Delta U = mL$

Gas Behavior and The First Law

Consider a gas in a cylinder with a movable piston. If the piston is pushed inward by an external force, work is done on the gas, adding energy to the system.

- From Chapter 9, the force exerted on the piston by the gas equals the pressure of the gas times the area of the piston: $F = PA$
- The work done equals the force exerted by the piston times the distance the piston moves: $W = Fd = PAd$

$$W = P\Delta V$$



Work by the gas is positive when expanding and negative when compressed.

Ideal Gas Law

For an "ideal" gas in which the molecules are far enough apart that we assume they do not interact with each other:

$$PV = NkT$$

P: Pressure

V: Volume

T: Temperature

N: The number of particles (molecules) of gas

$k = 1.381\times10^{-23}$ J/K (Boltzmann's Constant)

Temperature (T) must be given in Kelvin

Interactive Question

When the temperature of a quantity of gas is increased

A) the pressure must increase.
B) the volume must increase.
C) the pressure and/or the volume must increase.
D) none of the above.

Interactive Question

Two identical rooms in a house are connected by an open doorway. The temperatures in the two rooms are maintained at different values. Which room contains more air?

A) The room with the higher temperature
B) The room with the lower temperature
C) Neither because they both have the same volume
D) Neither because they both have the same pressure

Problem: A 2 liter bottle is filled with nitrogen (N_2) at STP and closed tight. (STP is "Standard Temperature and Pressure" of 273 K and 1 atm.)

(a) How many molecules of N_2 are there?

Problem: A 2 liter bottle is filled with nitrogen (N_2) at STP (Standard Temperature and Pressure of 1 atm and 273 K) and closed tight.

(b) If the temperature is raised to 100° C, what will be the new pressure.

Interactive Question

The Kelvin temperature of an ideal gas is doubled and the volume is halved. How is the pressure affected?

A) increases by a factor of 2
B) increases by a factor of 4
C) stays the same
D) decreases by a factor of 2
E) decreases by a factor of 4

Interactive Question

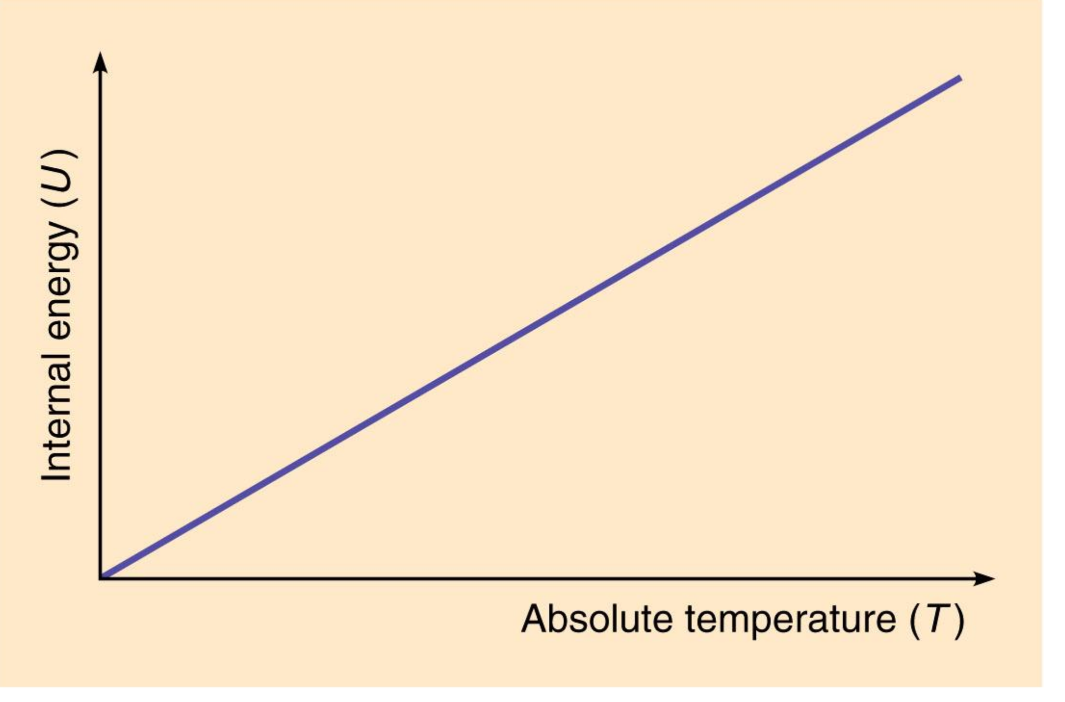
You fill your backpack with snacks and drive to the mountains to ski. When you get to the top of the mountain you notice that your bag of chips

A) looks just like it did when you packed it at home.
B) has shrunk and all of your chips are crushed.
C) has puffed up and looks like it could pop.

Internal Energy and Temperature

For an ideal gas, the internal energy is directly proportional to the temperature.

- Absolute temperature (Kelvin) must be used.
- The internal energy only depends on the kinetic energy of the molecules since there is no interaction between the molecules and no microscopic potential energy.



Interactive Question

The temperature of an ideal gas increases from 100 ºC to 500 ºC. What happens to the internal energy.

A) It decreases by 1/5
B) In increases by a factor of 5
C) It increases by a factor of 25
D) It stays the same
E) It just about doubles

Let's look at these two equations and describe some thermodynamic processes:

$$PV = NkT$$
$$Q = \Delta U + W$$

- **Adiabatic Process**: no heat flows into or out of the gas.
  - $Q = 0$
  - $\Delta U = -W = -P\Delta V = Nk\,\Delta T$
  - When the volume decreases the temperature increases even though no heat flows into the system.
- **Isothermal Process**: the temperature does not change.
  - $\Delta T = 0$
  - The internal energy must be constant since internal energy is proportional to temperature. i.e. $\Delta U = 0$
  - $Q = W$

Let's look at these two equations and describe some thermodynamic processes:

$$PV = NkT$$

$$Q = \Delta U + W$$

- **Isobaric Process**: the pressure of the gas remains constant.
  - $\Delta P = 0$
  - The internal energy increases as the gas is heated, and so does the temperature.
  - The gas also expands, removing some of the internal energy.
- **Isochoric Process**: the volume of the gas remains constant.
  - $W = 0$
  - $Q = \Delta U$

What can happen when heat is added to a system?

There are three possibilities

1) A temperature increase

   $Q = mc\Delta T$

2) A phase change

   $Q = mL$

3) An isothermal expansion

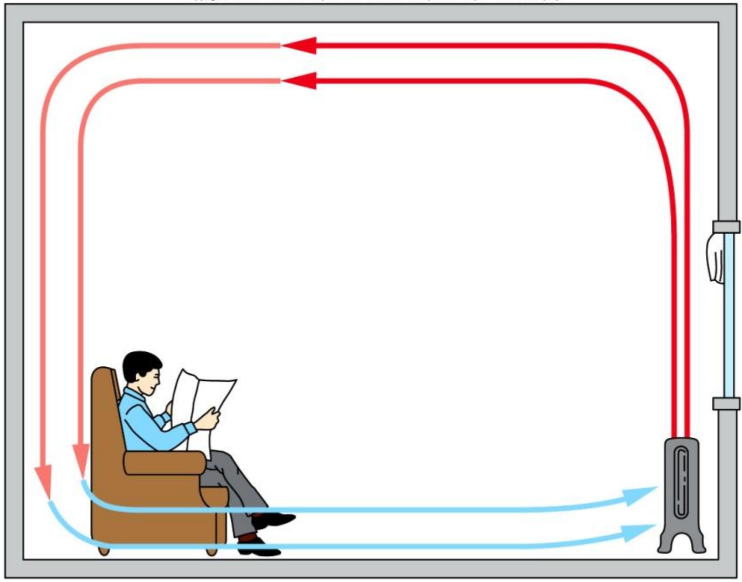
   $Q = W = P\,\Delta V$

Transfer of thermal energy

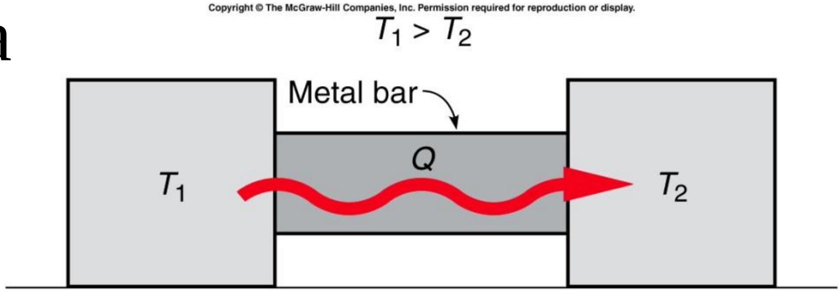
1) Convection: Mass carrying thermal energy is transported. “Hot air rises”
2) Conduction: Mass interacts to transport energy. Molecules may collide with other molecules. “Don’t grab a metal spoon that is partially submerged in hot water.”
3) Radiation: No mass is transported. Thermal energy is transported by electromagnetic radiation. “Always wear sunscreen.”

In ***convection***, heat is transferred by the motion of a fluid containing thermal energy.

- Convection is the main method of heating a house.
- It is also the main method heat is lost from buildings.



In ***conduction***, heat flows through a material when objects at different temperatures are placed in contact with one another.



- The rate of heat flow depends on the temperature difference between the objects and the *thermal conductivity* of the materials, a measure of how well the materials conduct heat.
  - Material with a high thermal conductivity allows heat to flow through it more easily.

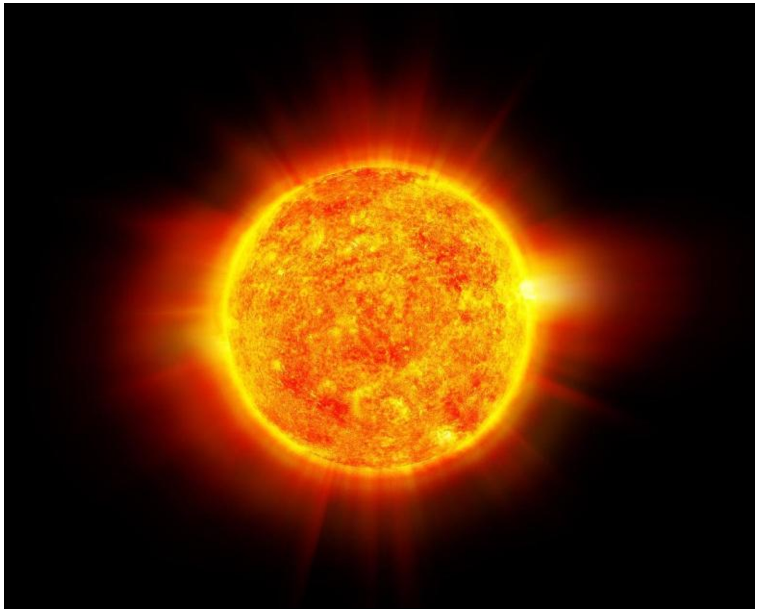
Interactive Question

When you get out of bed on a cold winter morning, a tile floor will feel colder than a carpeted floor. This is because:

A) A given mass of tile contains more heat than the same mass of carpet.
B) Tile conducts heat better than carpet.
C) Heat tends to flow from tile to carpet.
D) The temperature of the tile is lower than the temperature of the carpet.
E) The human body, being organic, resembles carpet more closely than it resembles tile.

In ***radiation***, heat energy is transferred by electromagnetic waves.

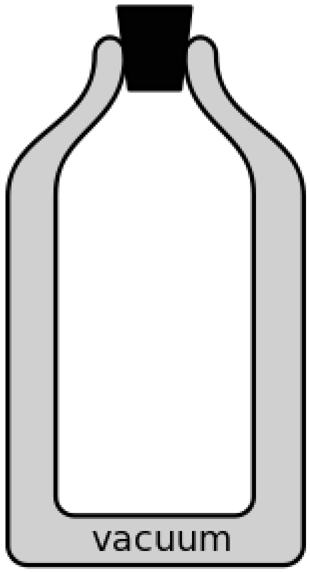
- Unlike conduction and convection, which both require a medium to travel through, radiation can take place across a vacuum.
  - Radiation is the only method to transfer heat through outer space.



Interactive Question

A thermos bottle works well because

A) Its glass walls are thin
B) Silvering reduces convection
C) Vacuum reduces heat radiation
D) Silver coating is a poor heat conductor
E) None of the above



Interactive Question

The heat transfer process in which heat flows directly through the material is

A) conduction

B) convection

C) radiation