Thermodynamics

I. Internal Energy
- energy of atoms and molecules
- thermal equilibrium
- ideal gas law
- temperature & kinetic theory

II. Heat
- thermal conductivity
- 1st law of thermodynamics
- heat engines & cycles
- 2nd law of thermodynamics

	The student will be able to:	HW:
1	Define and apply concepts of internal energy, thermal equilibrium, zeroth law of thermodynamics, and temperature.	1 – 3
2	State and apply the ideal gas law in terms of Boltzmann's constant and solve related problems with variables pressure, volume, and temperature.	4 – 7
3	State and apply the stipulations of the kinetic theory of gases and solve related problems involving pressure, force, kinetic energy, Boltzmann's constant, temperature, and speed distributions of particles	8 – 13
4	Define and apply the concept of thermal conductivity and solve related problems involving heat flow.	14 – 19
5	State and apply the first law of thermodynamics and solve related problems including work, heat, heat engines & cycles, P-V diagrams.	20 – 26
6	Define and describe entropy; state and apply qualitatively the second law of thermodynamics.	27 – 30

Internal Energy

- All material is thought to consist of atoms and molecules. These particles can have various types of potential and kinetic energy.
- The total energy of the atoms and molecules within a particular object or other defined quantity of matter is the internal energy (or thermal energy) of the system.
- Conservation of energy dictates that the internal energy of a system remain constant unless there is a transfer of energy or interaction with surroundings.

Internal Energy

- The amount of internal energy in a system or object depends on factors such as:
  - motion of atoms (translation, rotation, vibration)
  - phase (solid, liquid, gas, plasma)
  - chemical energy related to bonds
- The state of a system at a particular point in time may be specified by measures such as:
  - temperature
  - pressure
  - volume
- Changes in internal energy can be correlated with changes in state.

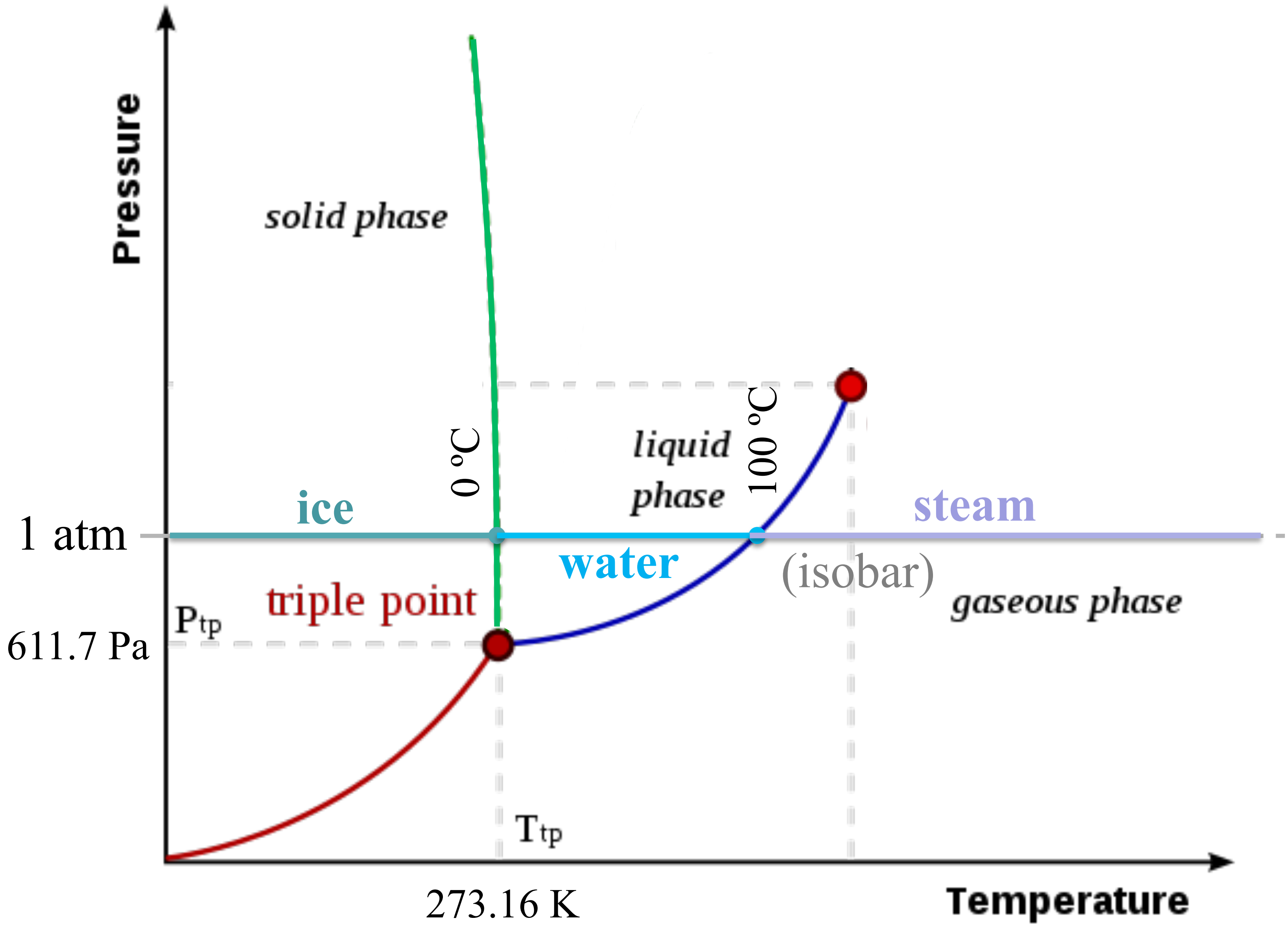


diagram credit: Matthieumarechal, Wikipedia

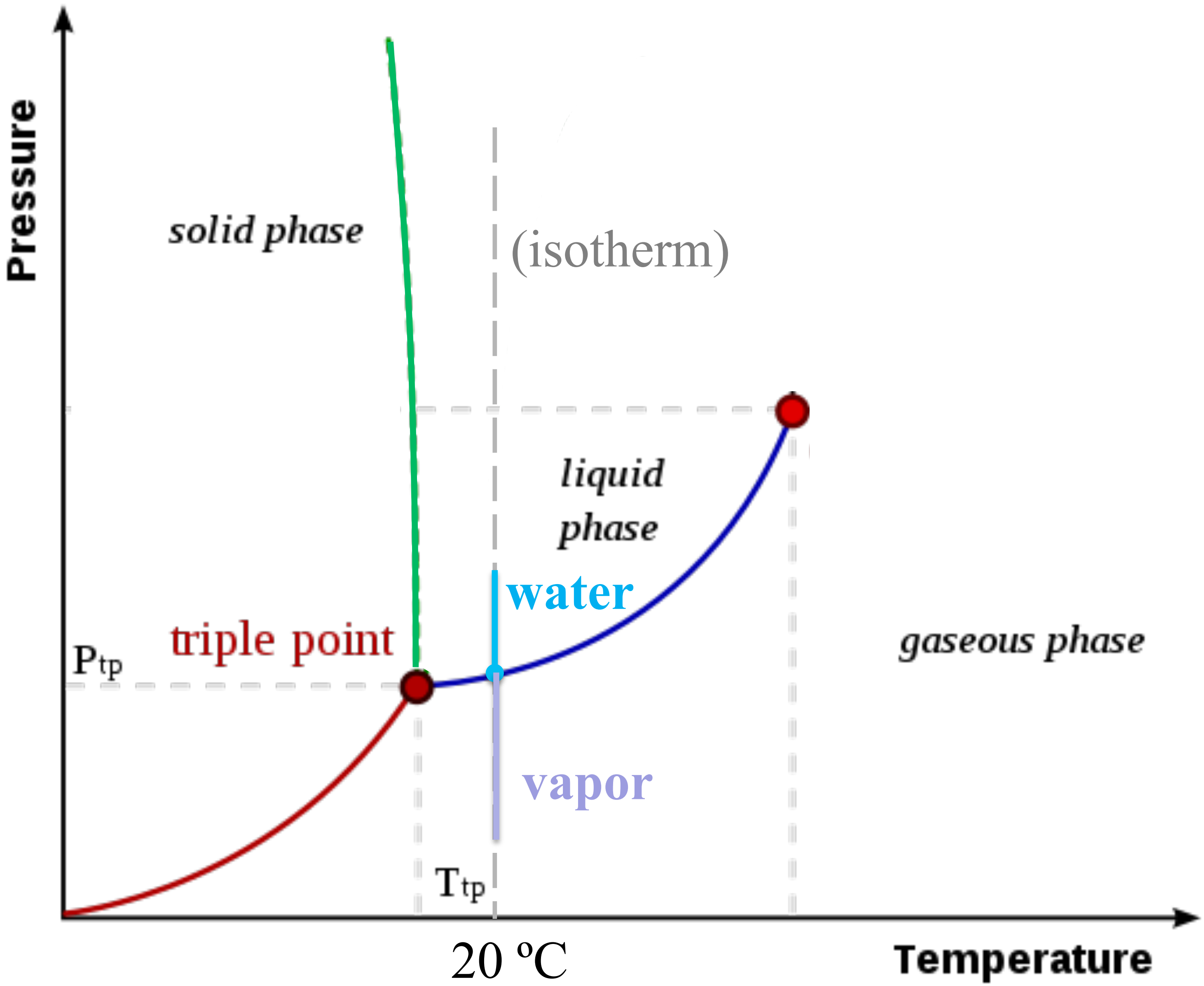


diagram credit: Matthieumarechal, Wikipedia

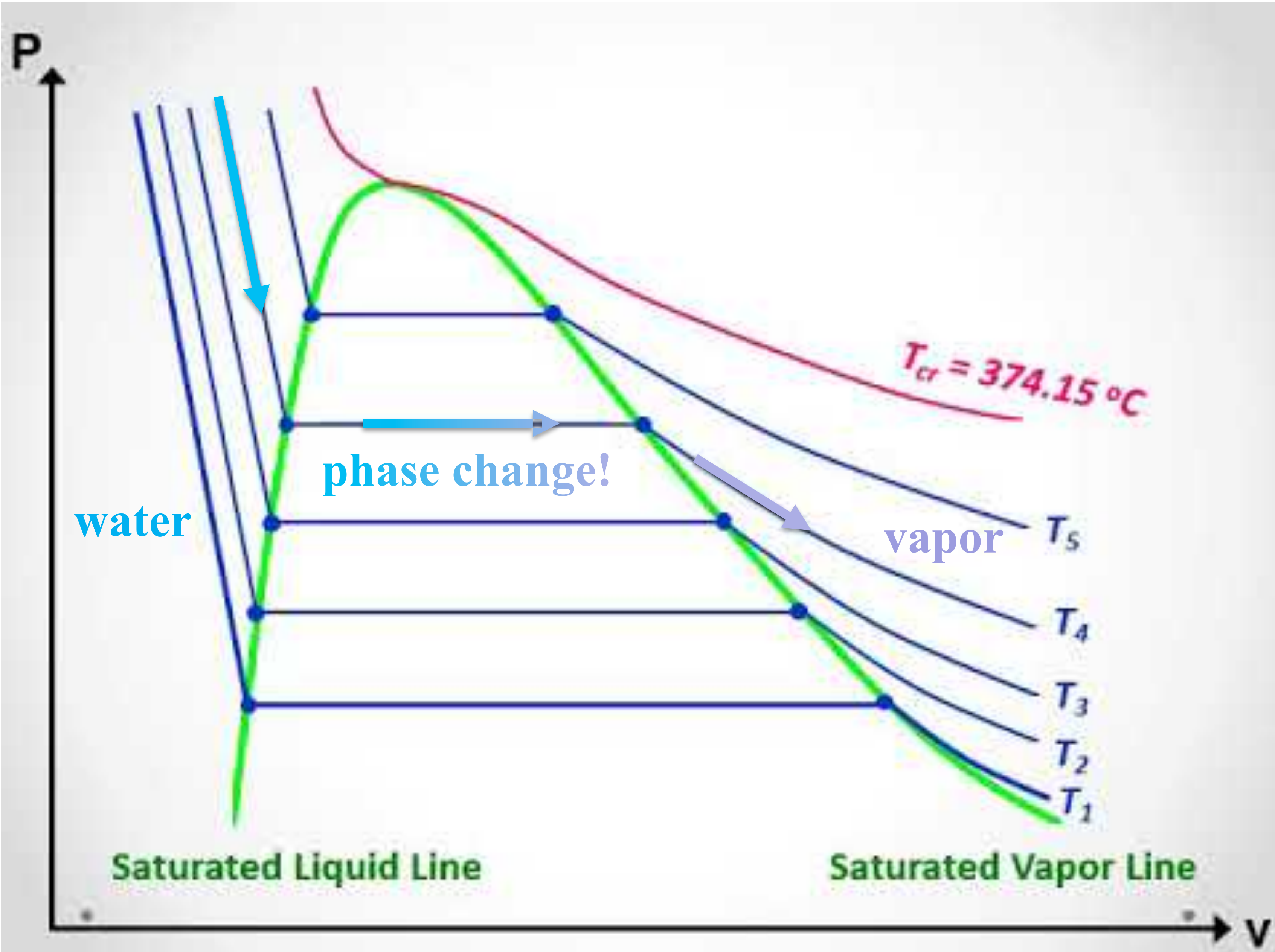


diagram credit: FL X, YouTube https://www.youtube.com/watch?v=oFKk25fX28o

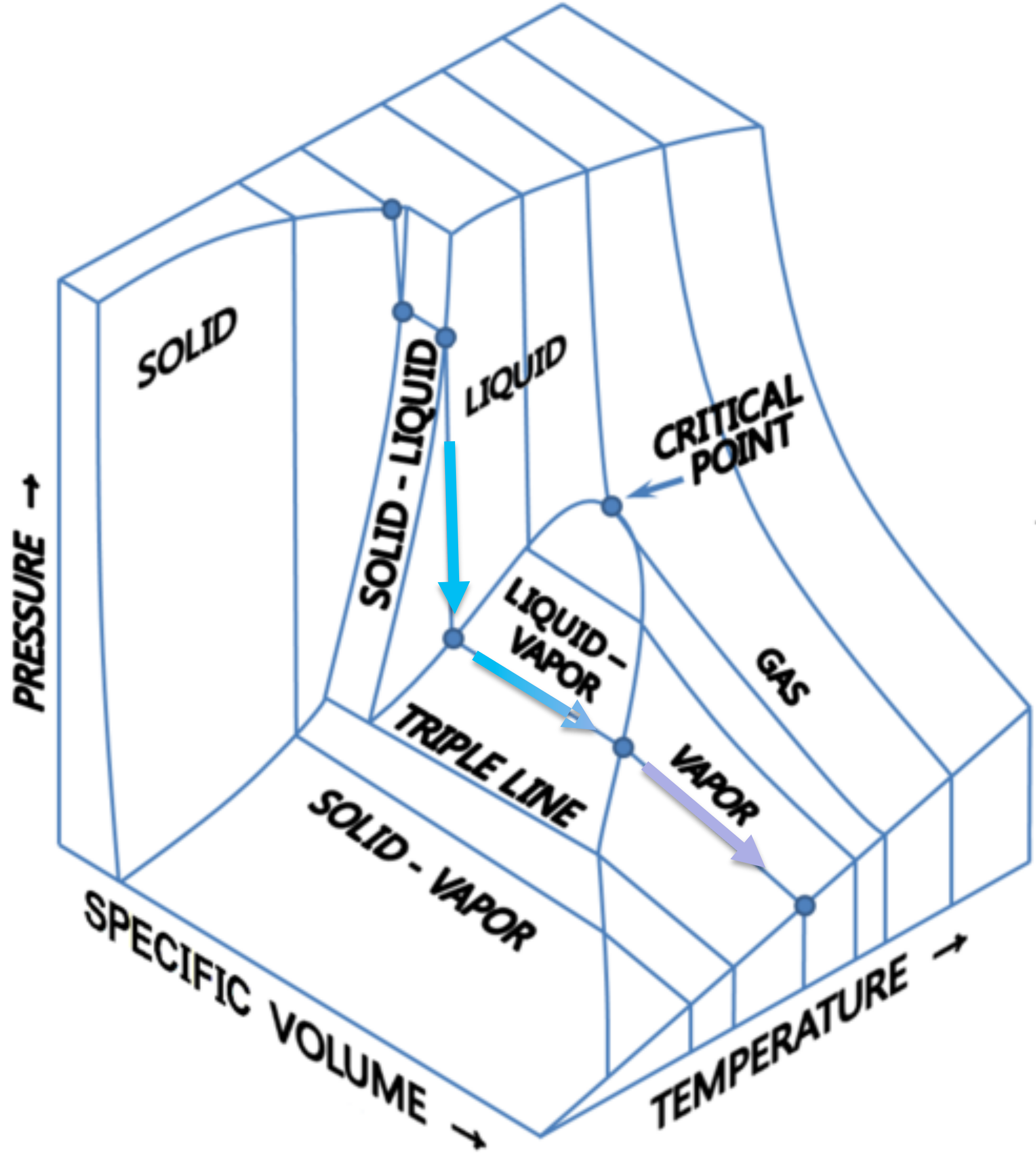


diagram credit: Donald L. Smith, H Padleckas, Kyu Ho Lee, Wikipedia

Temperature

- The temperature of a substance is a measure of "how hot" or "how cold", but also it relates to internal energy and state of matter.
- Common scales (related to water at 1 atm):

	freezing	boiling
Celsius (centigrade)	0.0 ºC	100.0 ºC
Fahrenheit	32.0 ºF	212 ºF
Kelvin	273 K	373 K

- Zero kelvin is the lowest possible temperature. Kelvin is an "absolute temperature" scale. On *this scale* temperature is a measure of…

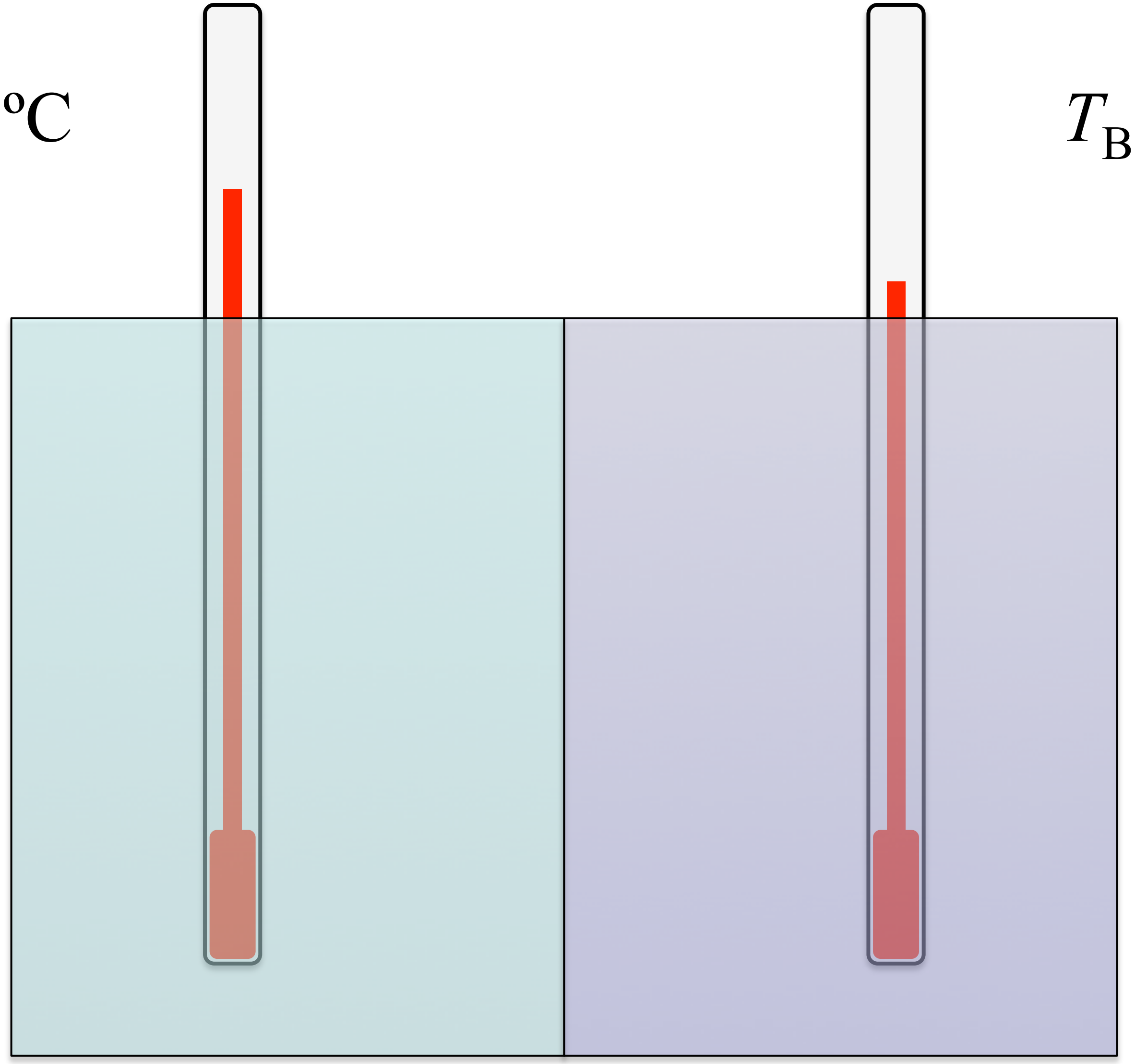
Temperature

- Absolute temperature is directly proportional to the average translational kinetic energy of the molecules in a substance.
- When two substances or objects with different temperatures are put into contact, energy transfers from the hotter to the colder until thermal equilibrium is reached with both substances at the same temperature.

Object or materials at different temperatures brought into contact…

$T_A = 20\ ^{o}C$

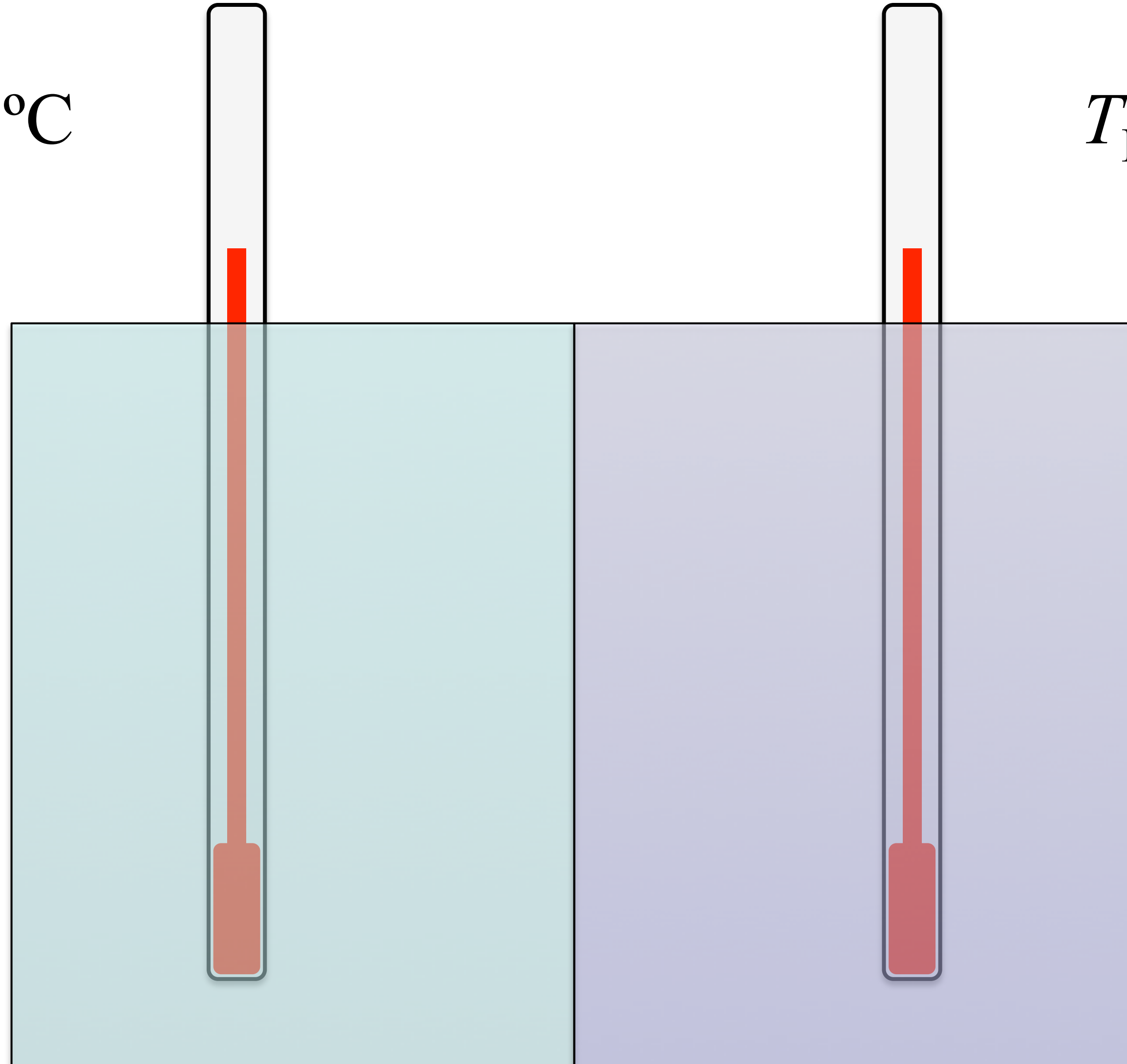
$T_B = 15\ ^{o}C$



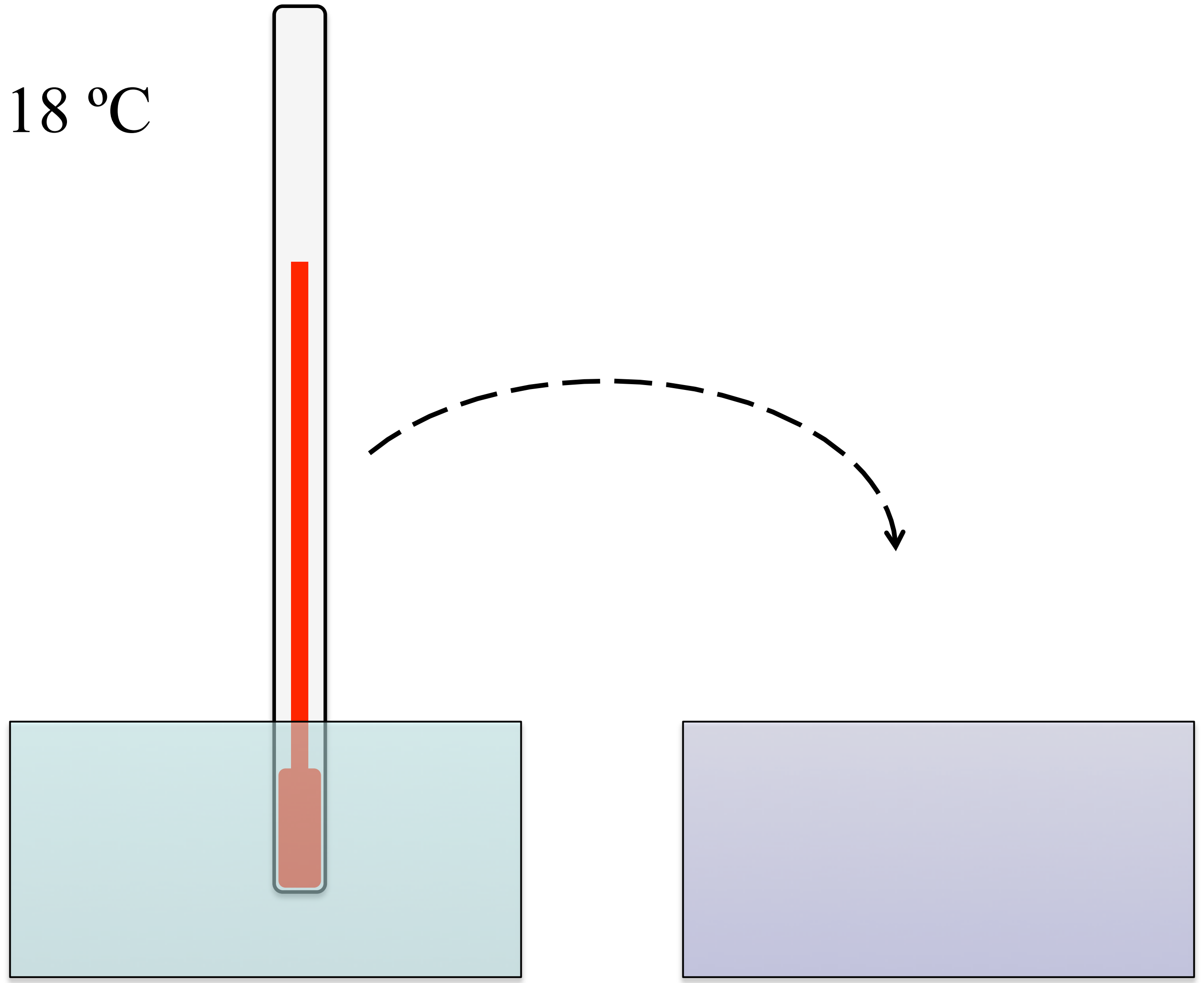
…reach a state of **Thermal Equilibrium** when temperatures are equal.

$T_A = 17\ ^{o}C$

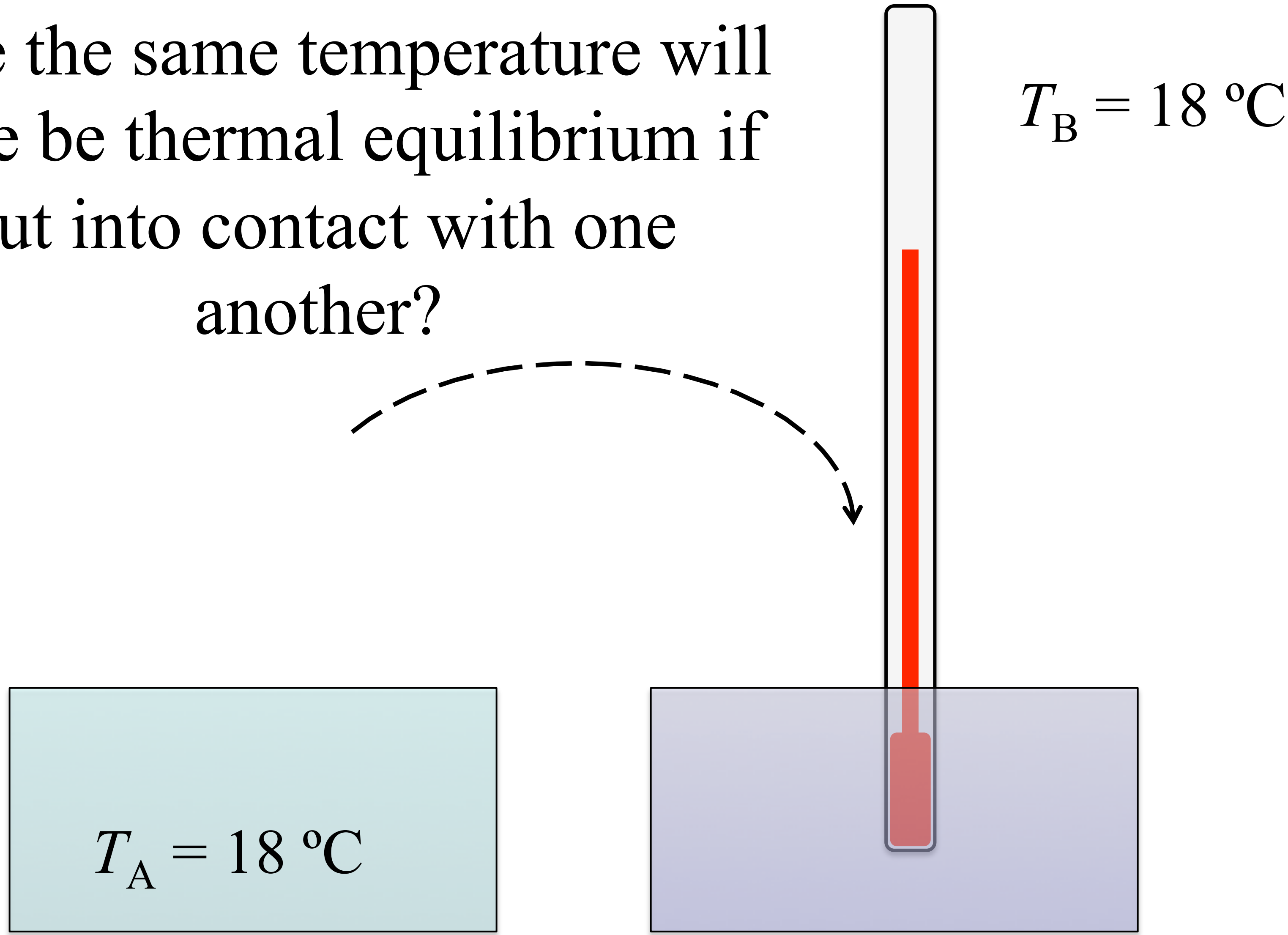
$T_B = 17\ ^{o}C$



$T_A = 18\ ^oC$



If two substances are measured to be the same temperature will there be thermal equilibrium if put into contact with one another?



Zeroth Law of Thermodynamics

- If two systems are each in thermal equilibrium with a third system, then the two systems are in thermal equilibrium with one another.
- The zeroth law is a necessary postulate to establish the concept temperature and its measurement.
- The "third system" can be thought of as a thermometer itself – like the previous few slides.
- While this seems obvious, it is not possible to prove and so its validity relies on repeated experimental observations.

	The student will be able to:	HW:
1	Define and apply concepts of internal energy, thermal equilibrium, zeroth law of thermodynamics, and temperature.	✓ 1 – 3
2	State and apply the ideal gas law in terms of Boltzmann's constant and solve related problems with variables pressure, volume, and temperature.	4 – 7
3	State and apply the stipulations of the kinetic theory of gases and solve related problems involving pressure, force, kinetic energy, Boltzmann's constant, temperature, and speed distributions of particles	8 – 13
4	Define and apply the concept of thermal conductivity and solve related problems involving heat flow.	14 – 19
5	State and apply the first law of thermodynamics and solve related problems including work, heat, heat engines & cycles, P-V diagrams.	20 – 26
6	Define and describe entropy; state and apply qualitatively the second law of thermodynamics.	27 – 30

Ideal Gas Law

An "ideal gas" is a useful model so long as pressure is not too great (well beyond an atm) and the temperature is not too low (near boiling point).

$$PV = nRT$$

where: P = pressure

V = volume

n = number of moles

T = temperature

R = universal gas constant

$$R = 0.0821 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}$$

$$R = 8.315 \frac{\text{J}}{\text{mol}\cdot\text{K}}$$

Ideal Gas Law

An "ideal gas" is a useful model so long as pressure is not too great (well beyond an atm) and the temperature is not too low (near boiling point).

$$PV = NkT$$

where: P = pressure

V = volume

N = number of molecules

T = temperature

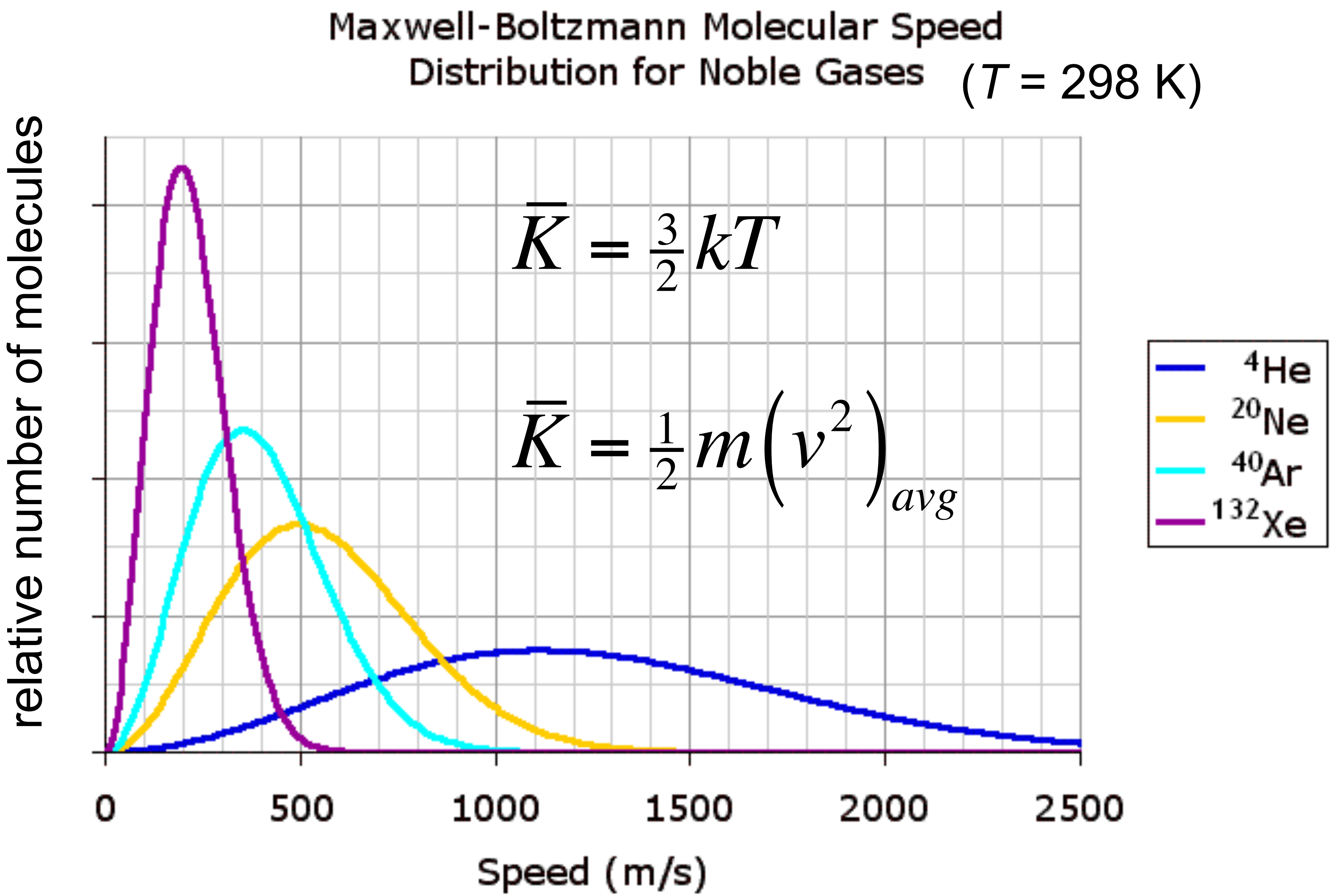
k = Boltzmann's constant

$$k = 1.38 \times 10^{-23}\ \tfrac{\text{J}}{\text{K}}$$

	The student will be able to:	HW:
1	Define and apply concepts of internal energy, thermal equilibrium, zeroth law of thermodynamics, and temperature.	✓ 1 – 3
2	State and apply the ideal gas law in terms of Boltzmann's constant and solve related problems with variables pressure, volume, and temperature.	✓ 4 – 7
3	State and apply the stipulations of the kinetic theory of gases and solve related problems involving pressure, force, kinetic energy, Boltzmann's constant, temperature, and speed distributions of particles	8 – 13
4	Define and apply the concept of thermal conductivity and solve related problems involving heat flow.	14 – 19
5	State and apply the first law of thermodynamics and solve related problems including work, heat, heat engines & cycles, P-V diagrams.	20 – 26
6	Define and describe entropy; state and apply qualitatively the second law of thermodynamics.	27 – 30

Kinetic Theory of Gases

- An ideal gas contains particles moving with random velocities.
- The average distance between particles is much greater than the size of the particles.
- The only significant interactions between particles are collisions, which are assumed to be perfectly elastic.
- Interactions with the walls of a container are also assumed to be perfectly elastic collisions.
- Using these assumptions the ideal gas laws can be derived using classical mechanics!

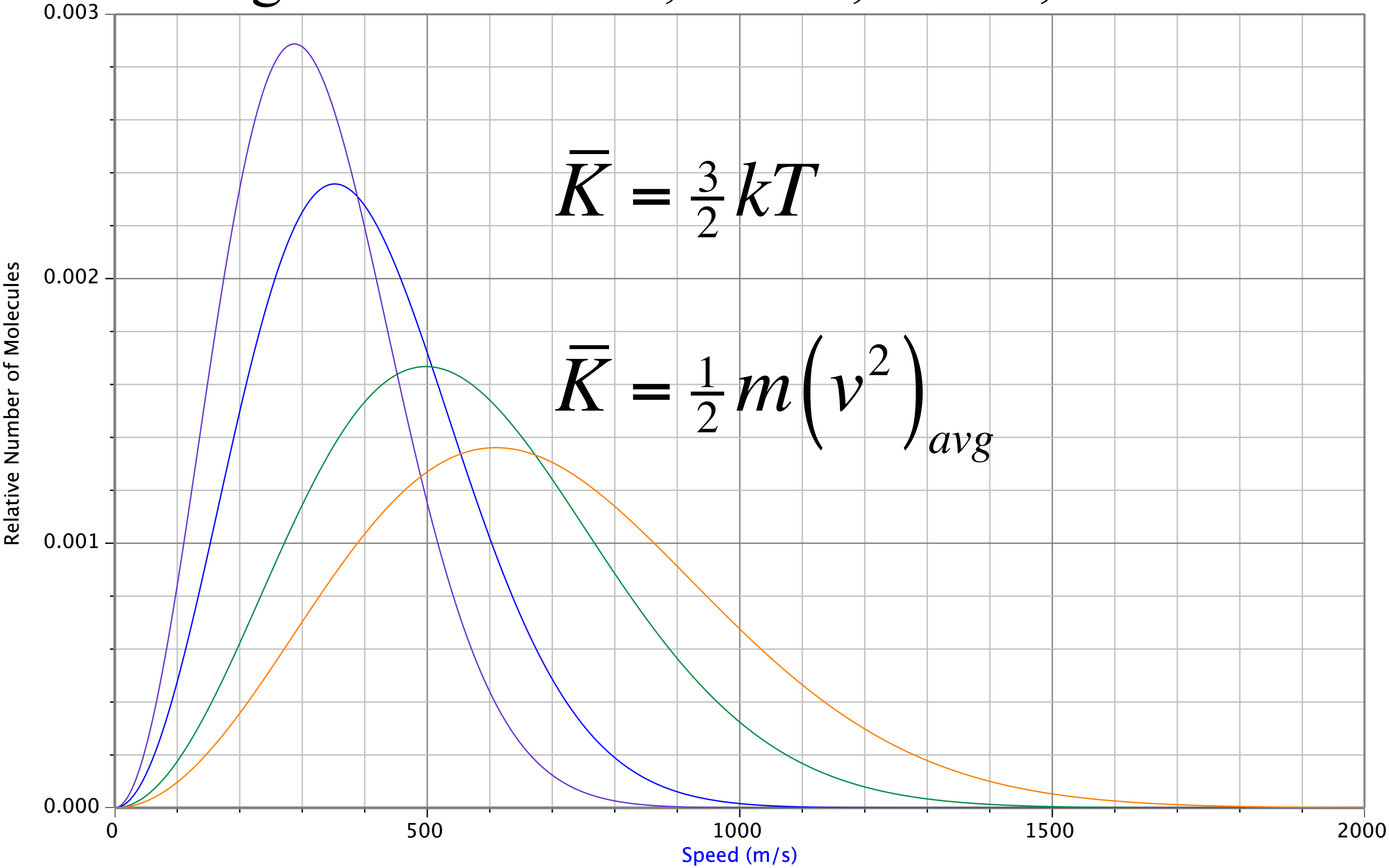


$$\bar{K} = \frac{3}{2}kT$$

$$\bar{K} = \frac{1}{2}m\left(v^2\right)_{avg}$$

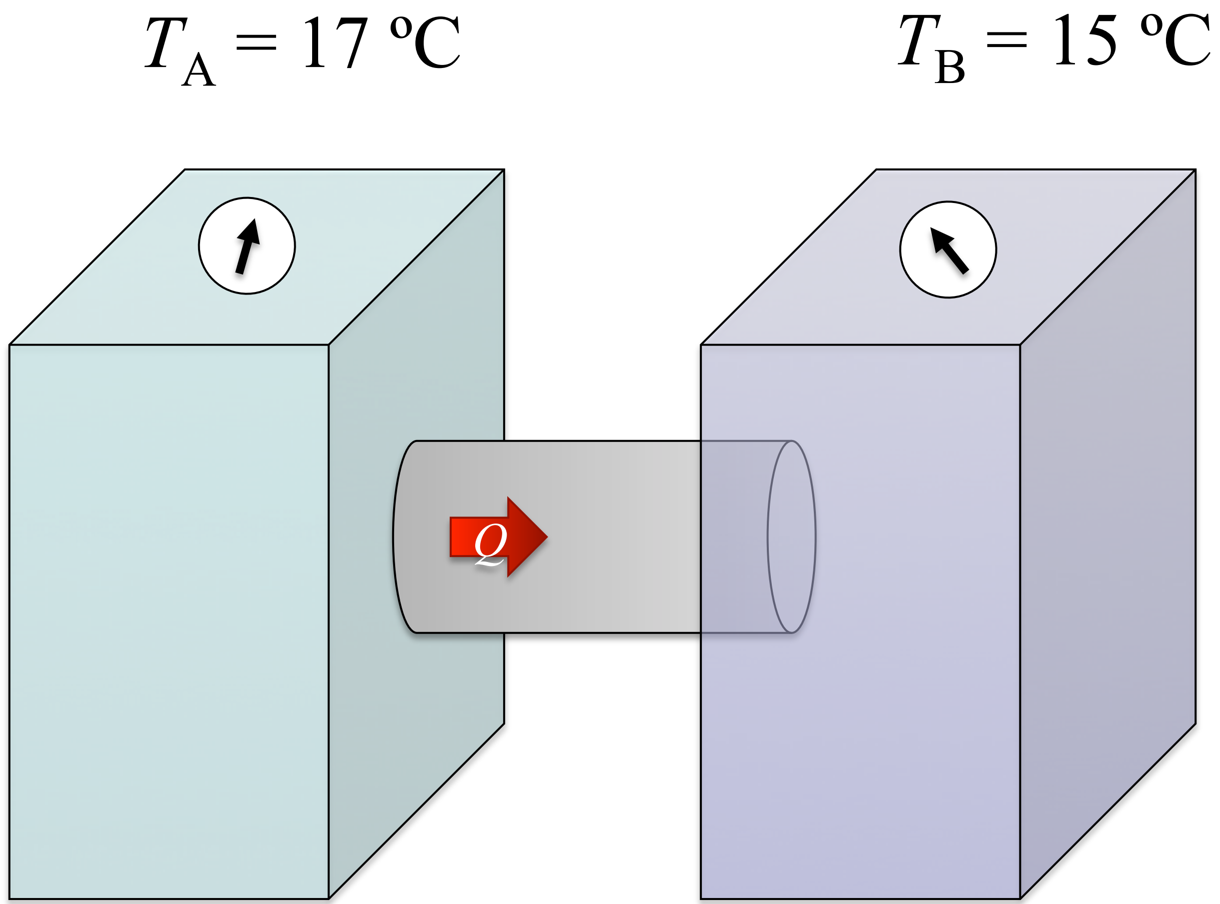
diagram credit: Pdbailey, Wikipedia

Argon-40 at 200 K, 300 K, 600 K, 900 K



	The student will be able to:	HW:
1	Define and apply concepts of internal energy, thermal equilibrium, zeroth law of thermodynamics, and temperature.	✓ 1 – 3
2	State and apply the ideal gas law in terms of Boltzmann's constant and solve related problems with variables pressure, volume, and temperature.	✓ 4 – 7
3	State and apply the stipulations of the kinetic theory of gases and solve related problems involving pressure, force, kinetic energy, Boltzmann's constant, temperature, and speed distributions of particles	✓ 8 – 13
4	Define and apply the concept of thermal conductivity and solve related problems involving heat flow.	14 – 19
5	State and apply the first law of thermodynamics and solve related problems including work, heat, heat engines & cycles, P-V diagrams.	20 – 26
6	Define and describe entropy; state and apply qualitatively the second law of thermodynamics.	27 – 30

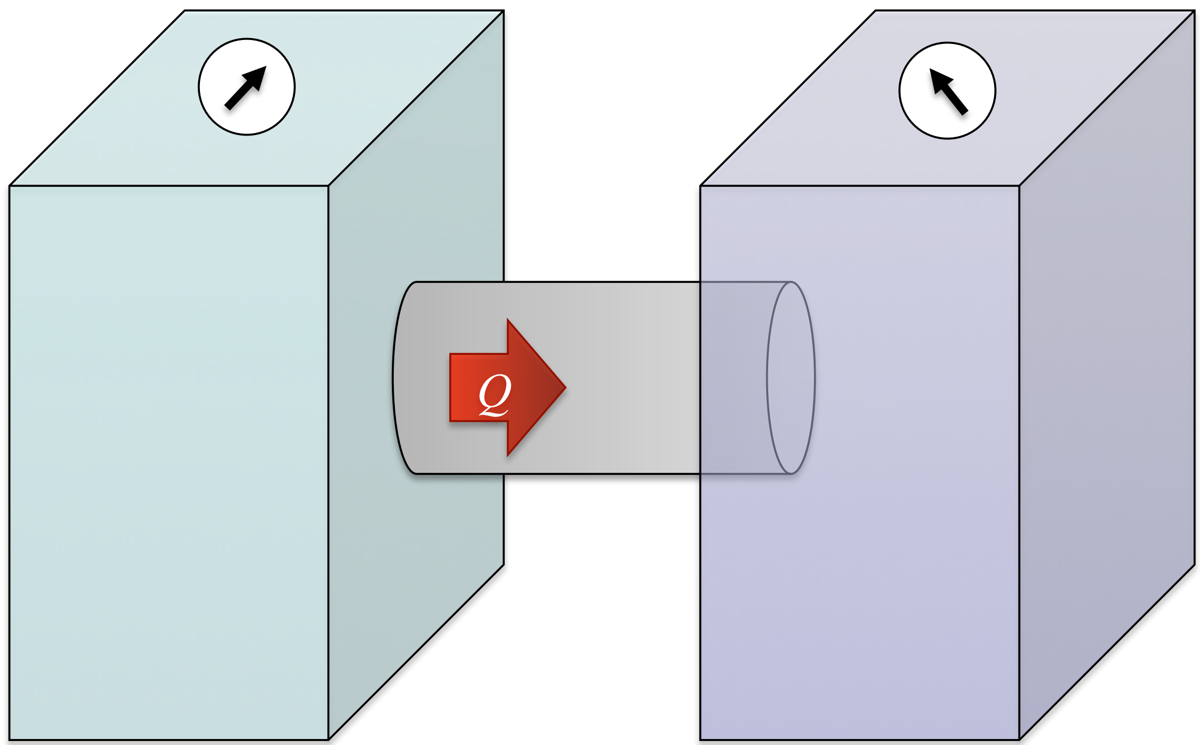
What governs the rate at which energy flows?



What governs the rate at which energy flows?

Greater temperature difference,…

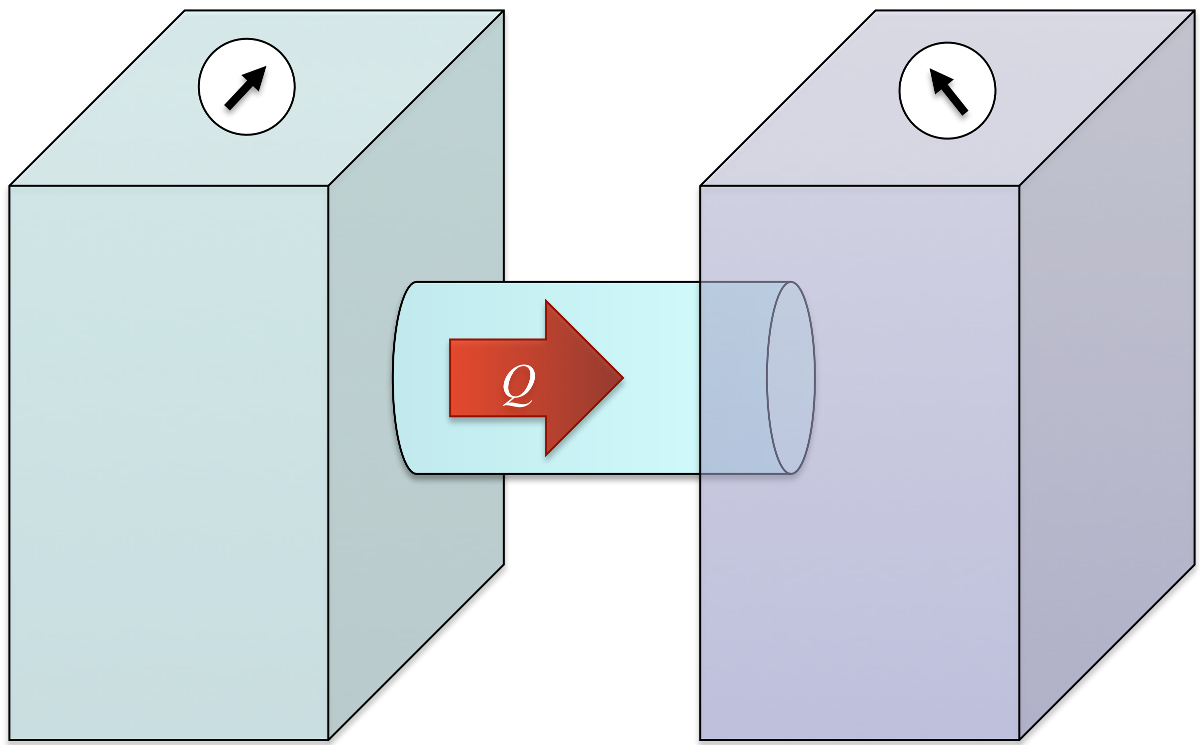
$T_A = 20$ ºC $T_B = 15$ ºC



What governs the rate at which energy flows?

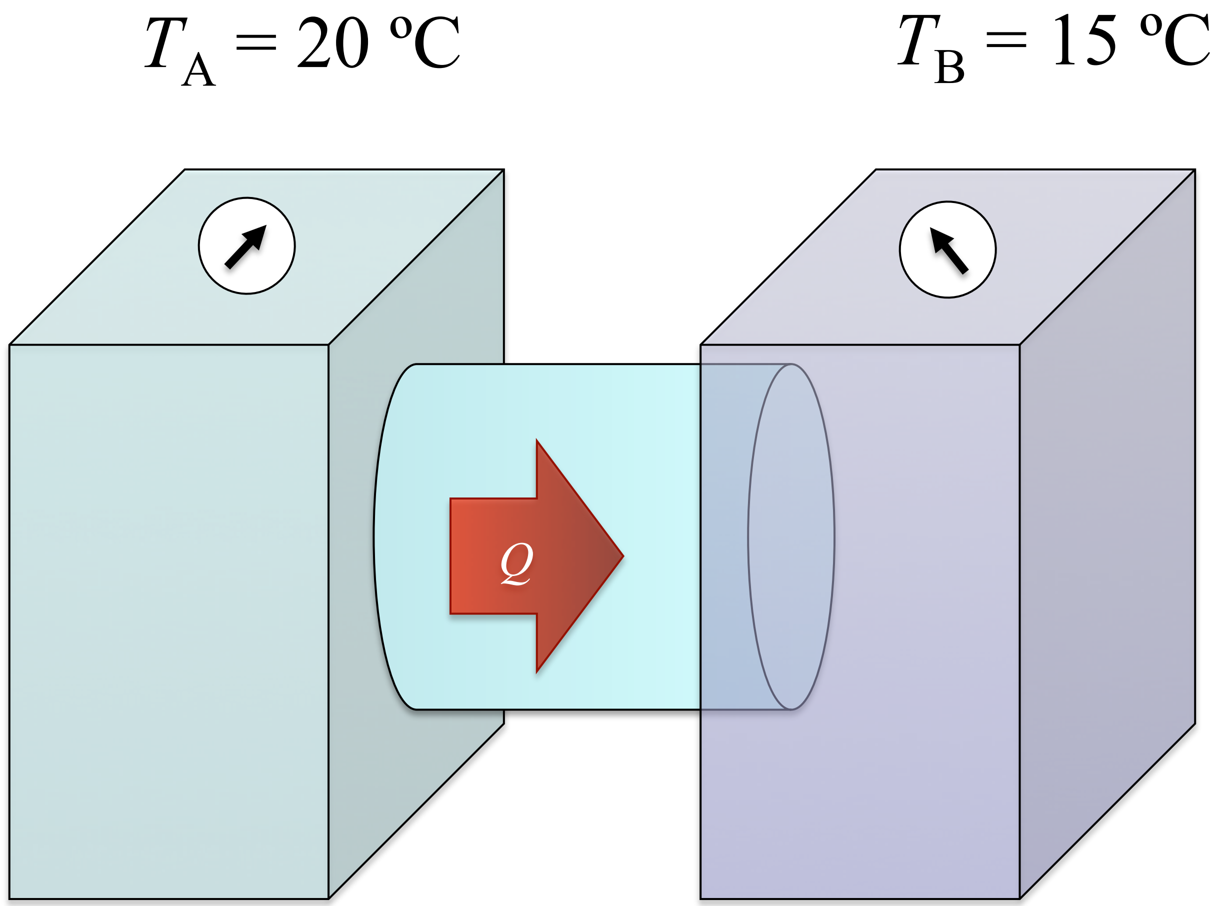
…, better heat conducting material,…

$T_A = 20$ ºC $T_B = 15$ ºC



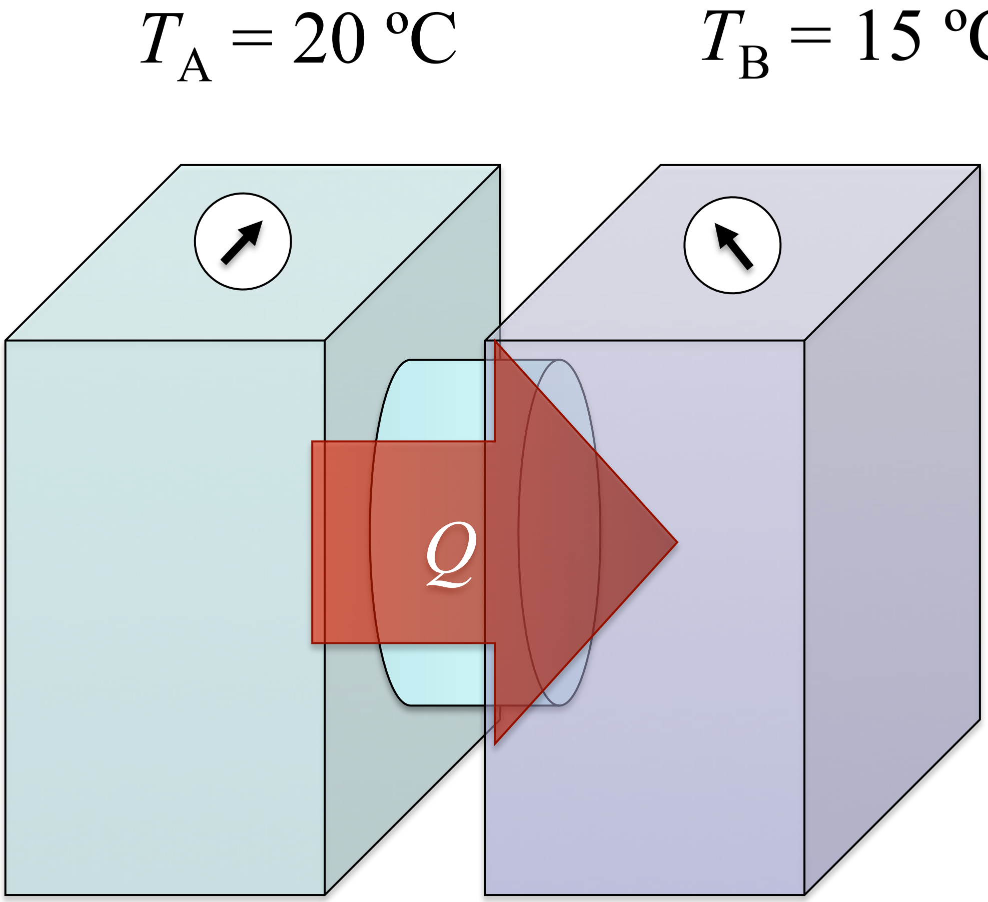
What governs the rate at which energy flows?

…, greater cross-sectional area,…



What governs the rate at which energy flows?

…, or shorter length, all lead to greater heat flow!



Thermal Conductivity

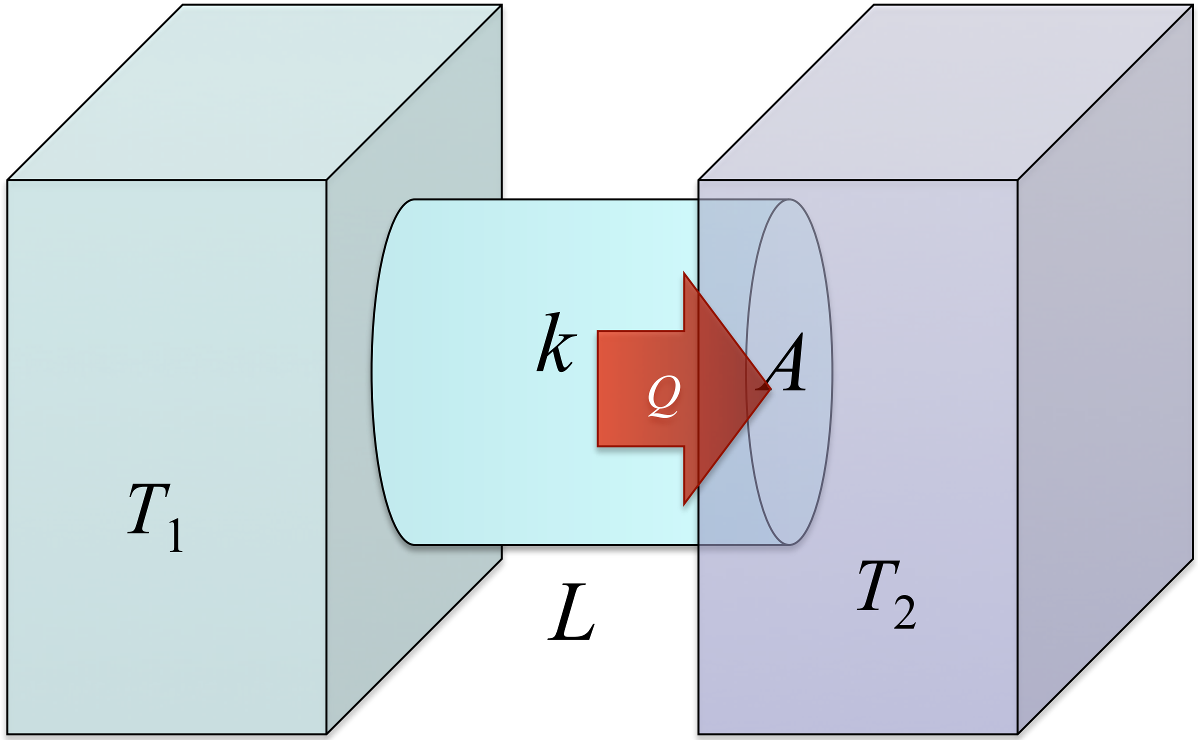
- Heat is the transfer of thermal energy by convection, radiation, or conduction.
- Conduction when thermal energy is "transmitted" through a material from a higher temperature "source" to a lower temperature "sink".
- The rate at which energy is transferred is a function of the type of material and its dimensions. Greater flow rate will occur with greater cross sectional area and/or less length.
- Metals are generally good thermal conductors. Poor thermal conductors are called insulators – materials such as plastics, air, Styrofoam, etc.

Thermal Conductivity

The rate of heat flow by means of conduction can be modeled as a function of temperature difference and characteristics of the material:

$$\frac{Q}{\Delta t} = \frac{kA\Delta T}{L}$$

where: Q = heat
k = thermal conductivity
A = cross-sectional area
T = temperature
L = length



$$\frac{Q}{\Delta t} = \frac{kA\Delta T}{L}$$

Material	Thermal conductivity, k (J/s·m·K)
Silver	420
Copper	380
Aluminum	230
Steel	40
Ice	2
Glass	0.84
Water	0.56
Wool	0.042
Air	0.023