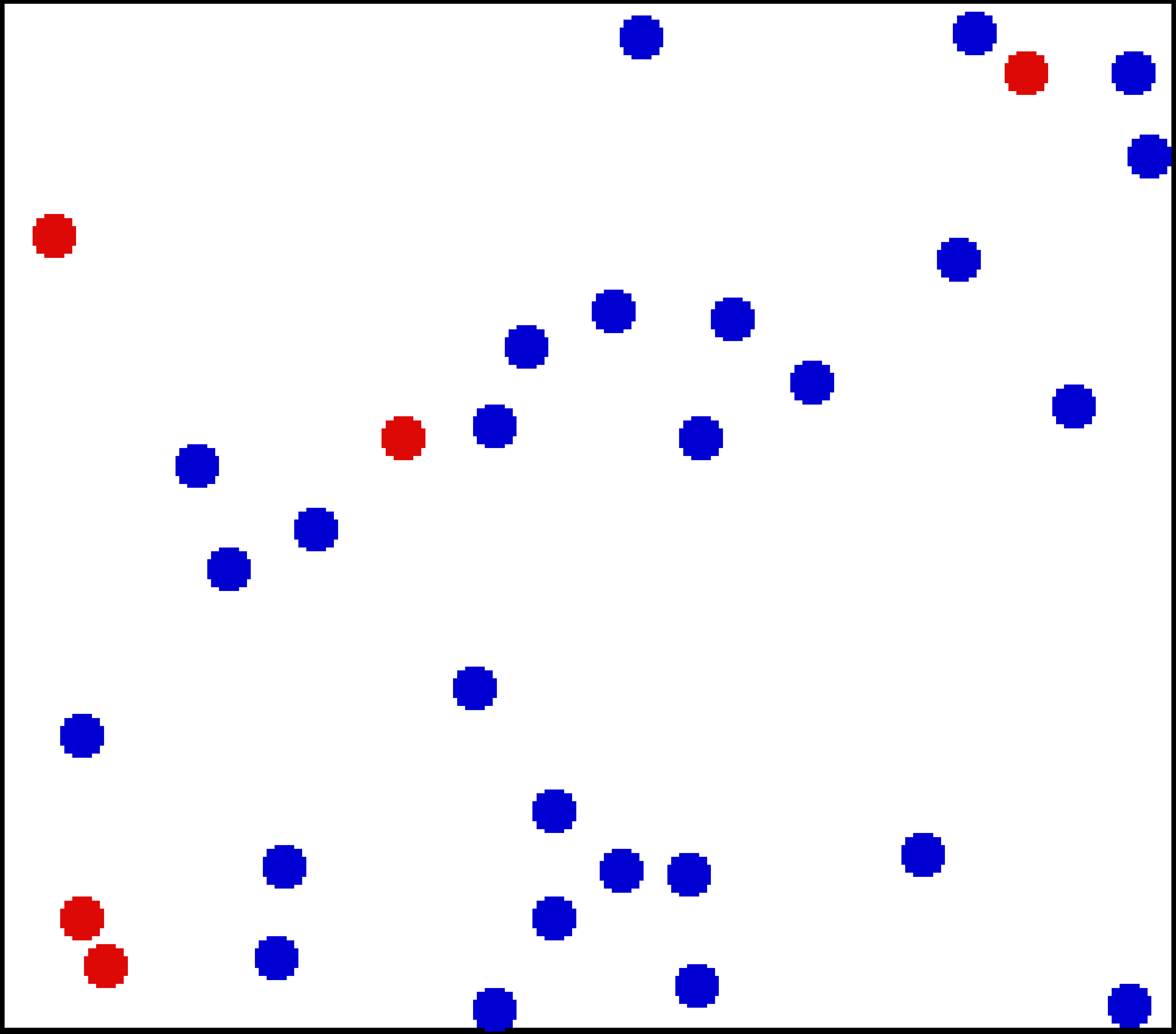
K20: Temperature, Heat, and How Heat Moves

- Definition of Temperature
- Definition of Heat
- How heat flows
- (Note: For all discussions here, “particle” means a particle of mass which moves as a unit. It could be a single atom (like the noble gas Argon in our atmosphere), or a molecule (like CO2) made up of atoms bound together. It may or may not have internal vibrational etc. motions as well.
- “fluid” means a liquid, or a gas

Imagine a Gas….



$$\frac{3}{2}kT = \frac{1}{2}m < V^2 >$$

The temperature of a large assembly of particles is proportional to the **kinetic energy per particle** in a simple way for an atmosphere. (a "particle" here being an atom, or a molecule

k = Boltzmann's constant

m = mass of the particle (for us here, usually an atom or a molecule)

$<V^2>$ is the average of the squared velocities of all the particles

T = the temperature in Kelvins

The Thermal Energy of an Object (its “Heat”), Can Flow from One Place to Another, by Three Different Mechanisms

1. Radiation

2. Conduction

3. Convection

Heat Transfer by Radiation

- Photons have energy, which they carry away from their source, and deposit where the photon is absorbed.
- How? One way, we have already examined: electrons falling to a lower energy level in an atom, or molecular vibration/rotation energy level going to a lower level. This emits a photon which can be absorbed by another atom/molecule and put it into an excited state.

Mean Free Path

- The emitted photons in a materials move in random directions until they are scattered or absorbed
- The "**mean free path**" length is how far the photon, on average, travels between emission and absorption or scattering off another particle
- The **denser** the medium, the **shorter** the <u>mean free path</u>, and the <u>slower</u> will radiation be able to move heat from one place to another
- Radiation moves freely (large **mean free path**) at the top of the atmosphere, and a very short mean free path inside a solid.

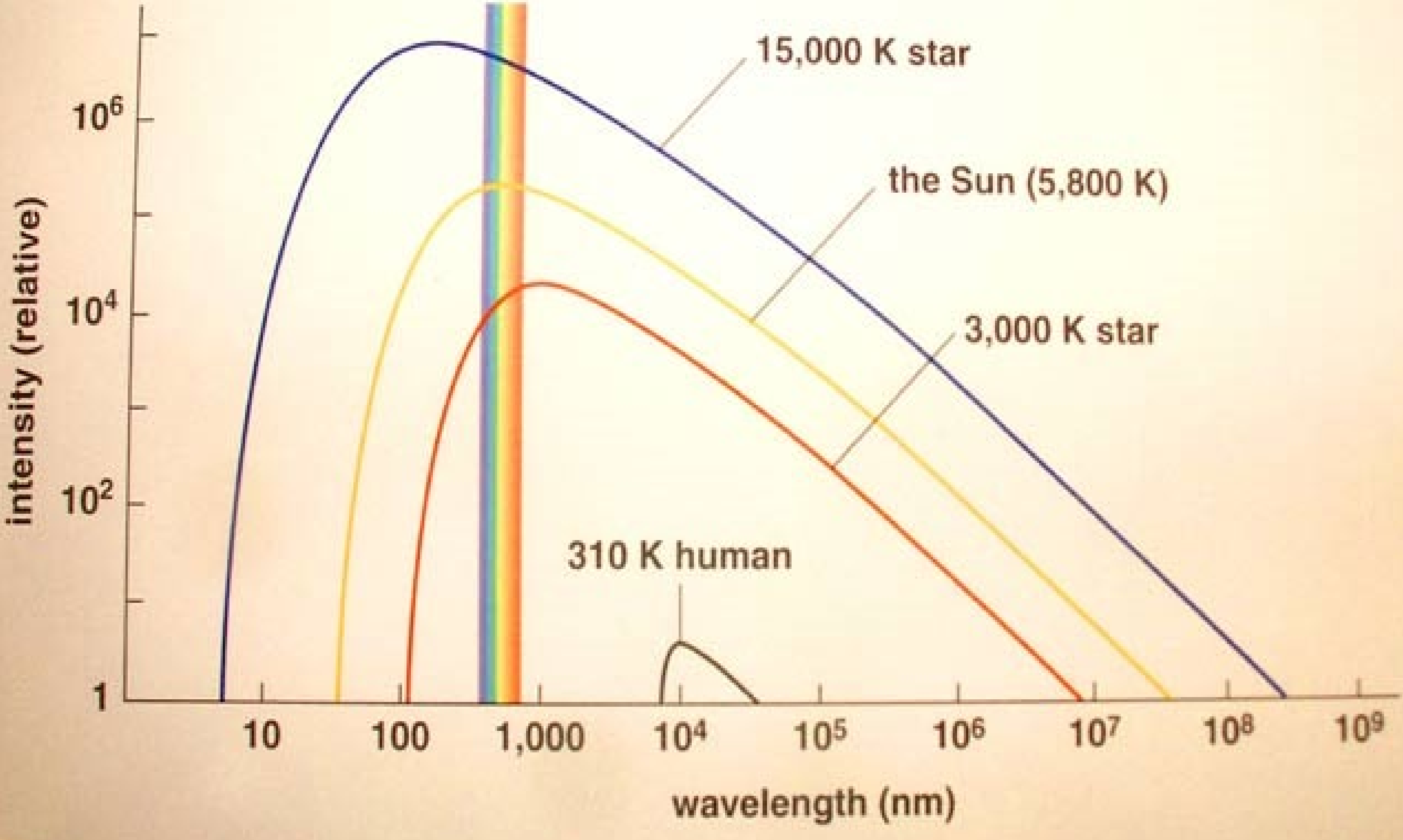
Thermal radiators in the Real World emit a broad thermal spectrum according to this version of the Stefan-Boltzmann equation…

$$\frac{L}{A} = \varepsilon \sigma T^4$$

(Why the little “**ε**= emissivity”? A perfect blackbody lets its interior photons emerge perfectly, but in a real object, the photons excite motions in the electron shells (especially for metals, whose outer electrons are poorly bound to the atom) which can absorb or reflect the photon energy, so that the probability for it to emerge is less than 100%. Such an object has an **emissivity factor “ε”** which is less than 1. A third option for a photon, besides being absorbed or reflected, is simply to pass through the material without interaction (transparency), glass is an obvious example. Atmospheres can be partially transparent as well, depending on the wavelength of light.

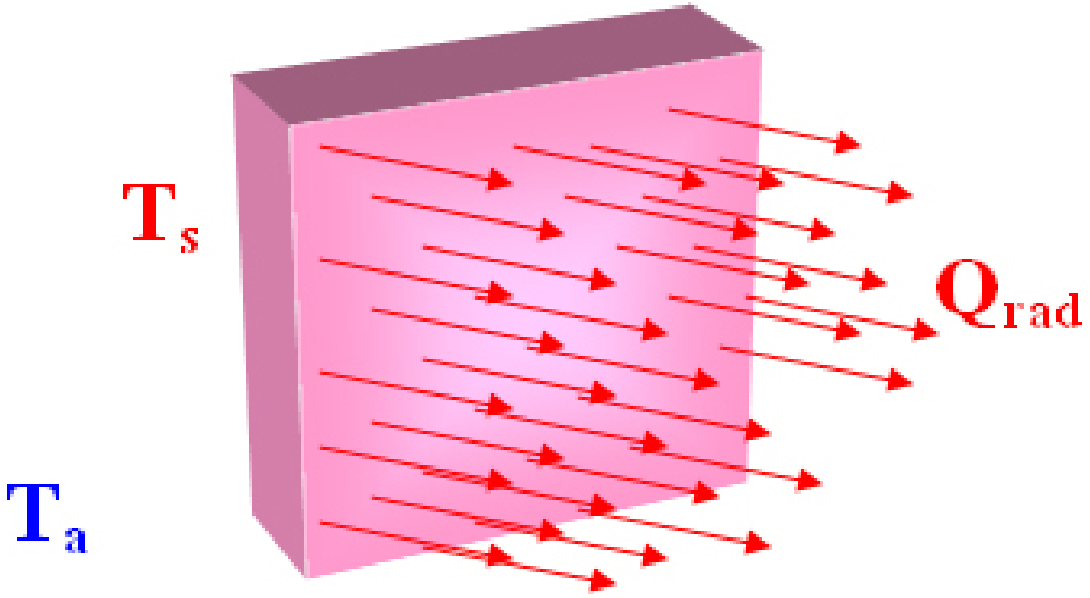
ε for insulators tends to be near 1, but for metals, especially shiny ones, **ε** can be small, less even than 0.1.

Figure 6.10 Graphs of idealized thermal radiation spectra



The hotter object will radiate more than the cooler object and so the net flow of heat is always from "hotter to colder"

$$Q_{rad} = \varepsilon\sigma A(T_s^{\,4} - T_a^{\,4})$$



$$\sigma = 5.67\times10^{-8}\,\frac{W}{m^2K^4}$$

Heat Transfer by Conduction: Particle-banging-against-Particle

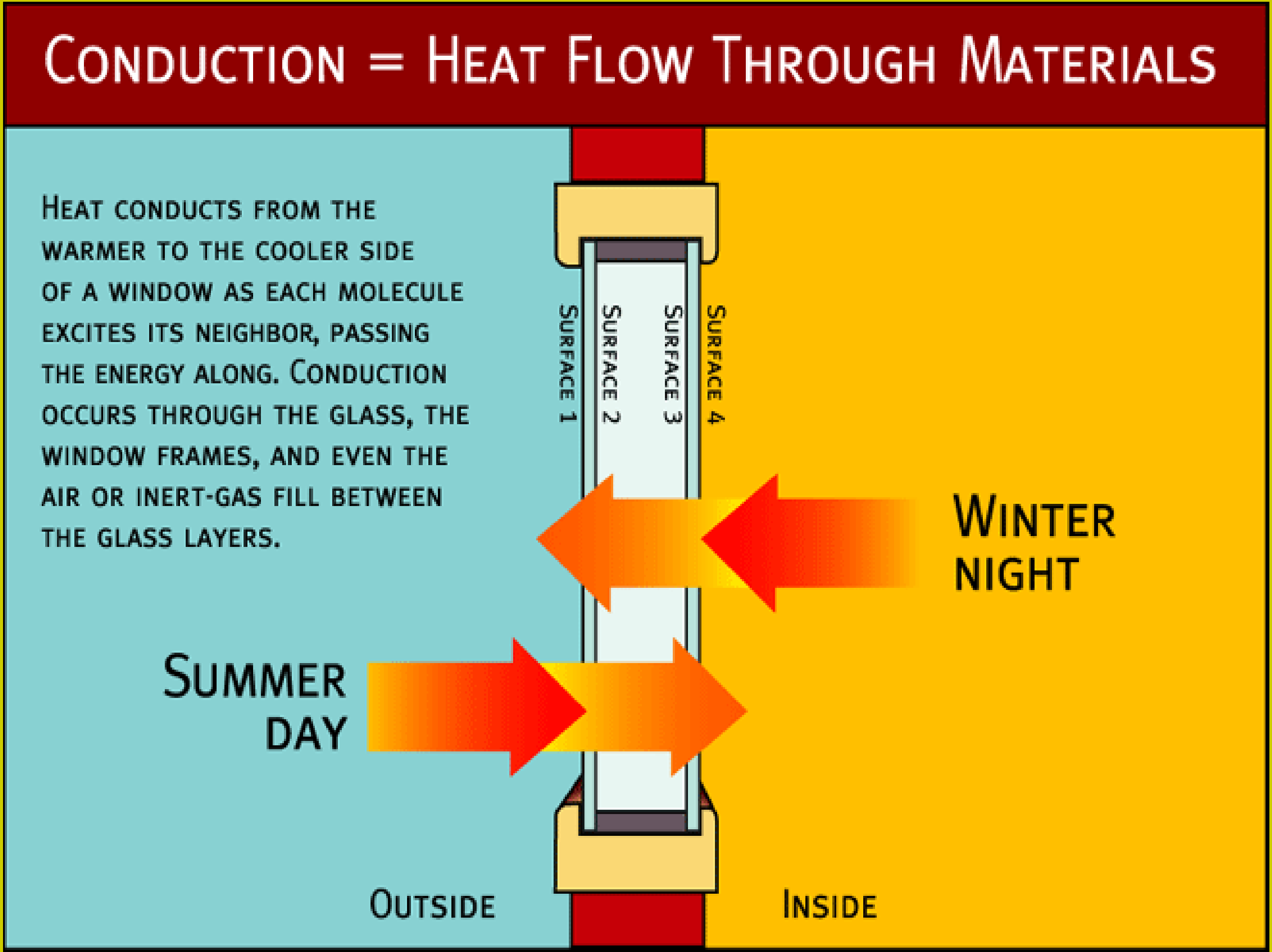
- This is the simplest to understand. Moving particles bang up against neighbors who in turn bang up against their neighbors, jostling them, etc.
- Faster moving particles will on average slow down when they hit a slower mover, and the slower mover will speed up when hit by a faster mover, thus transferring kinetic energy
- So the fast-jiggling particles on the hot side have spent some of their energy by making their slower neighbors jiggle more
- Meaning, those neighbors are now hotter, and the fast-jiggling particles are now cooler than they were.

$$q = -k\,A\,\frac{dT}{dX}$$

- The rate at which heat flows by conduction is proportional to the gradient (dT/dX) in the temperature, to the conductivity (k) of the material, and the area (A) across which the heat is flowing.
- Conductivity **k**; (related to the “R factor” for insulation materials. R ~1/k). Some materials allow this bumping together of neighboring atoms more easily than other materials.

Metal has a very **high k, low R**
Styrofoam has a very **low k, and high R**

Heat always moves from hotter towards cooler. Conduction moves heat by particle-banging-against particle, whether the particles are gas molecules, atoms in a glass, wood in a door frame…

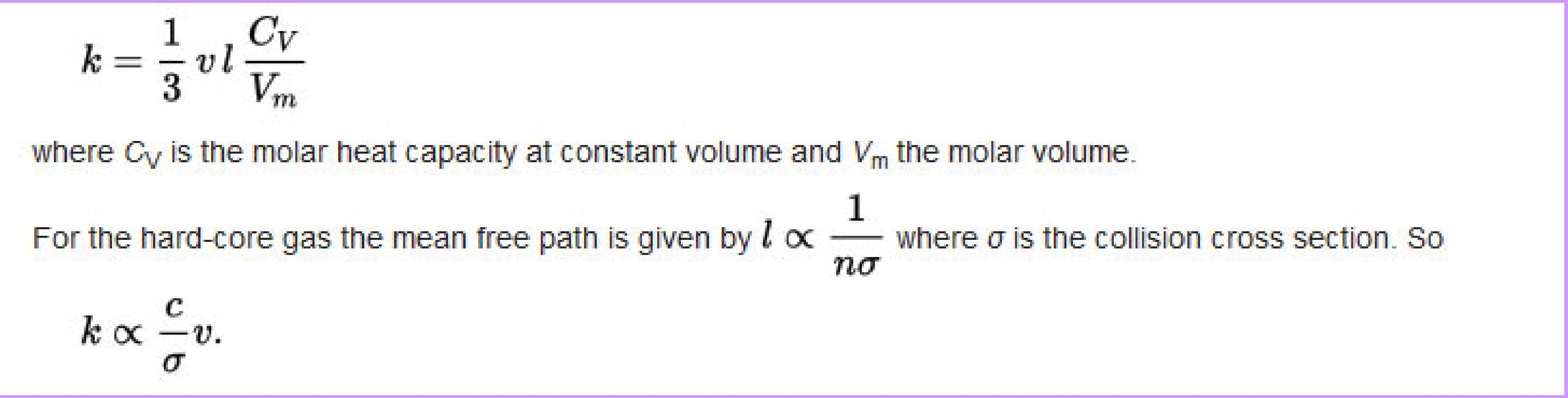


CONDUCTION = HEAT FLOW THROUGH MATERIALS

HEAT CONDUCTS FROM THE WARMER TO THE COOLER SIDE OF A WINDOW AS EACH MOLECULE EXCITES ITS NEIGHBOR, PASSING THE ENERGY ALONG. CONDUCTION OCCURS THROUGH THE GLASS, THE WINDOW FRAMES, AND EVEN THE AIR OR INERT-GAS FILL BETWEEN THE GLASS LAYERS.

Heat flow by conduction is <u>less</u> in <u>low density</u> solids

- However, for atmospheres it’s more complicated…
- While there are more collisions in a denser medium, the mean free path is also shorter in a compensating way
- So, heat conduction in a gas which has typical atmosphere conditions, turns out to be more or less independent of density.



$$k = \frac{1}{3} v l \frac{C_V}{V_m}$$

where C_V is the molar heat capacity at constant volume and V_m the molar volume.

For the hard-core gas the mean free path is given by $l \propto \frac{1}{n\sigma}$ where σ is the collision cross section. So

$$k \propto \frac{c}{\sigma} v.$$

The thermal conductivity k of a gas

…where v is the velocity of the gas molecules, l is the mean free path, C_v is the thermal capacitance of the gas, and V_m is the volume in question, where both C_v and V_m should be taken with the same volume. (source Click the link for alternative but equivalent formulae if this is confusing).

Simplifying further, if the gas atoms have no internal degrees of freedom to excite and can be considered as little hardballs, then the conductivity is just proportional to the velocity (*i.e.* roughly the square root of the temperature). Hotter gases have higher thermal conductivity, other things being equal.

The point above to note, is that the density of the gas doesn't enter the equation, because the mean free path is inversely proportional to the density, while the mean free path itself enters in the numerator, and so cancels out of the equation altogether, in this situation.

“R Value” and Insulation

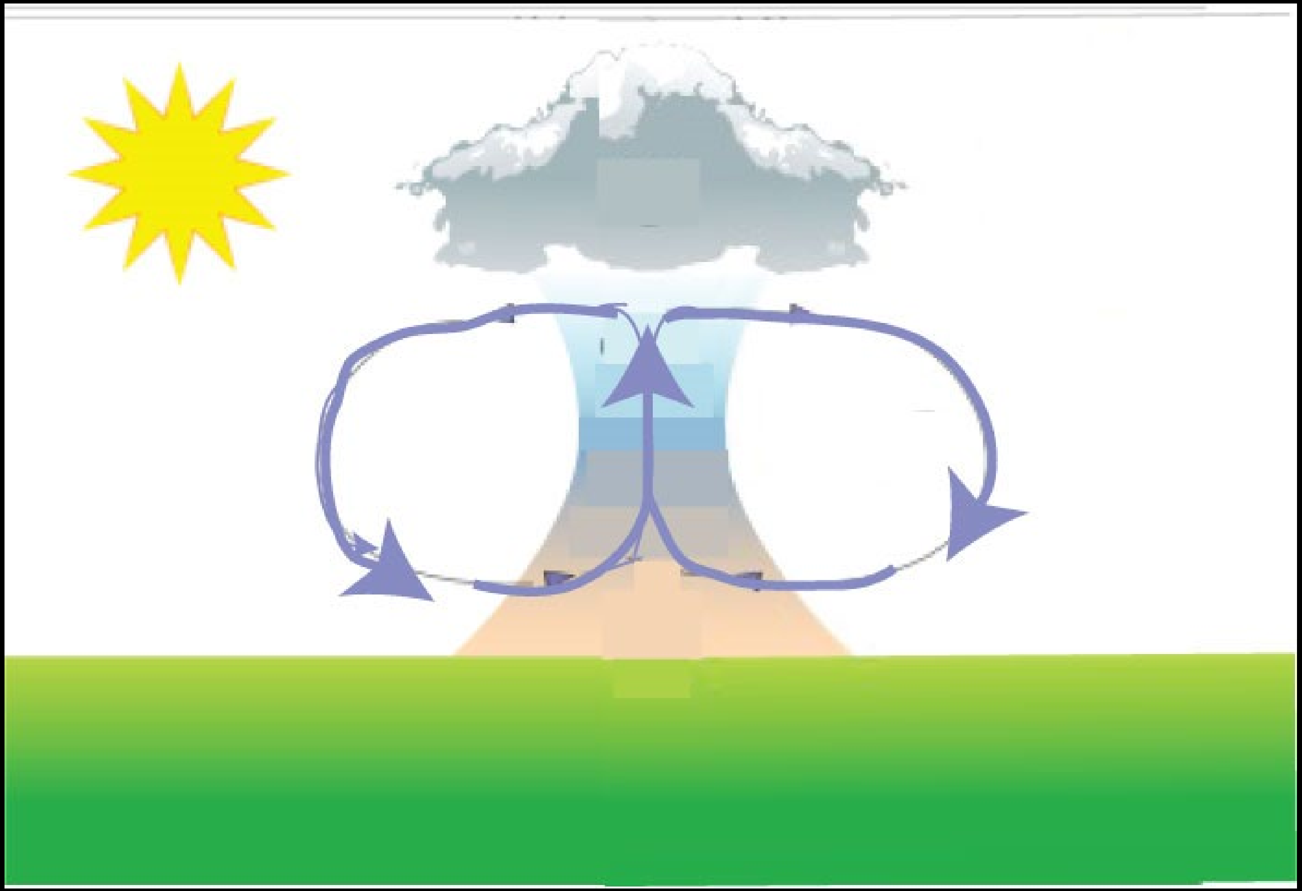
- Engineers, physicists think in terms of **conductivity k**, but marketers of insulation to consumers (e.g. Home Depot) like to think in terms of “R Value”, because they want you to see a **bigger** R value when they ask you to pay **more**. Pay more, get more! Get it?
- “R value”, like for your thermal windows is thermal resistance. Higher R, higher thermal resistance
- Adding greenhouse gases to the atmosphere means more absorption of outgoing Infrared radiation from the ground, so the “R value” of the atmosphere goes up.
- ***By adding CO2, we are adding insulation, in a sense, to the Earth; adding “R value”***

Heat Transfer and the Medium It Happens In

- Both conduction and convection require a medium (some sort of <u>mass</u>, like a gas, or liquid, or for conduction, a solid).
- Radiation heat transfer, however, will happen best when there's no medium to get in the way of the photons)
- Usually, conduction is MOST efficient in a dense medium, and radiation is LEAST efficient in a dense medium.

Heat Transfer by Convection

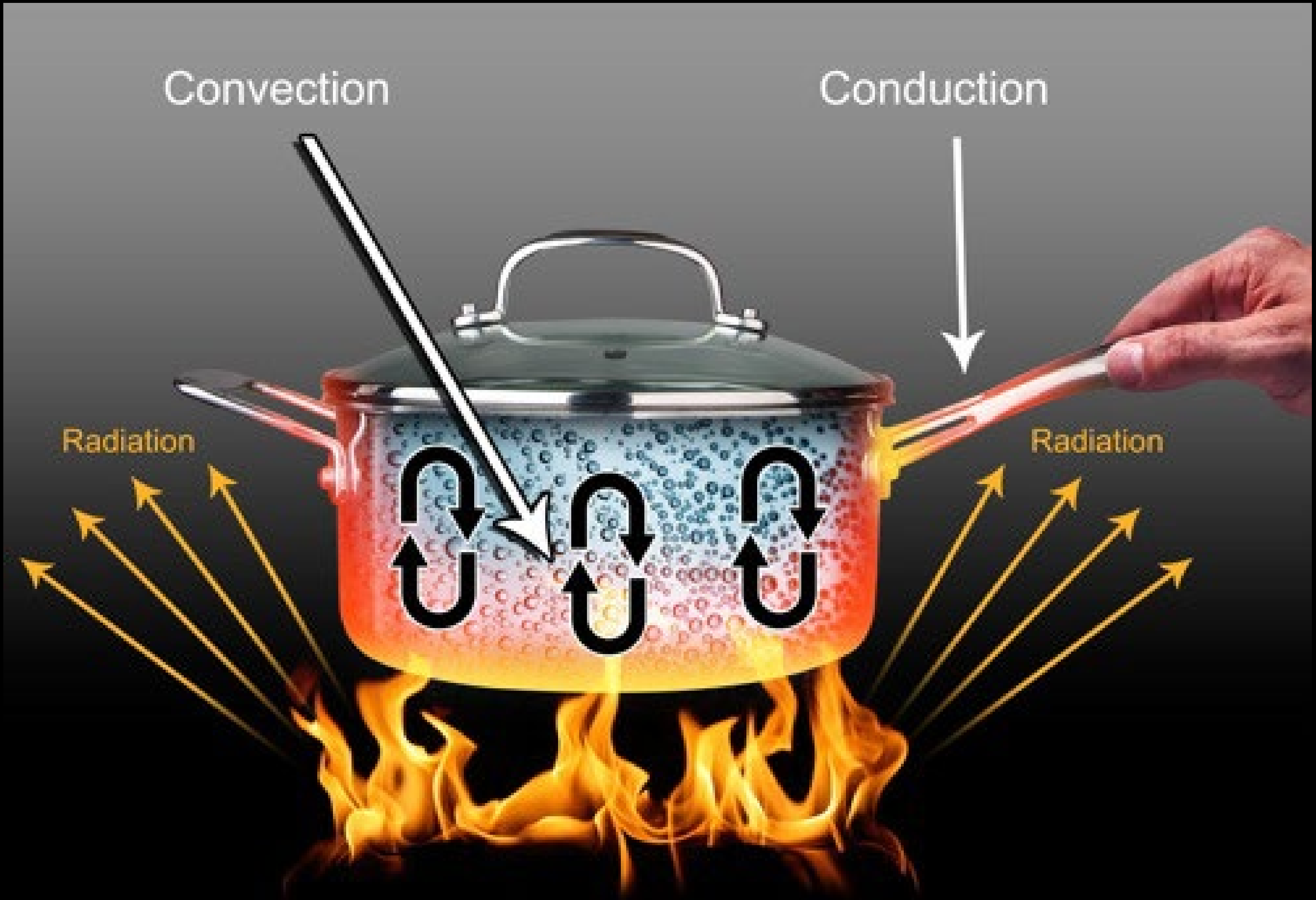
- So, how does convection differ from conduction?



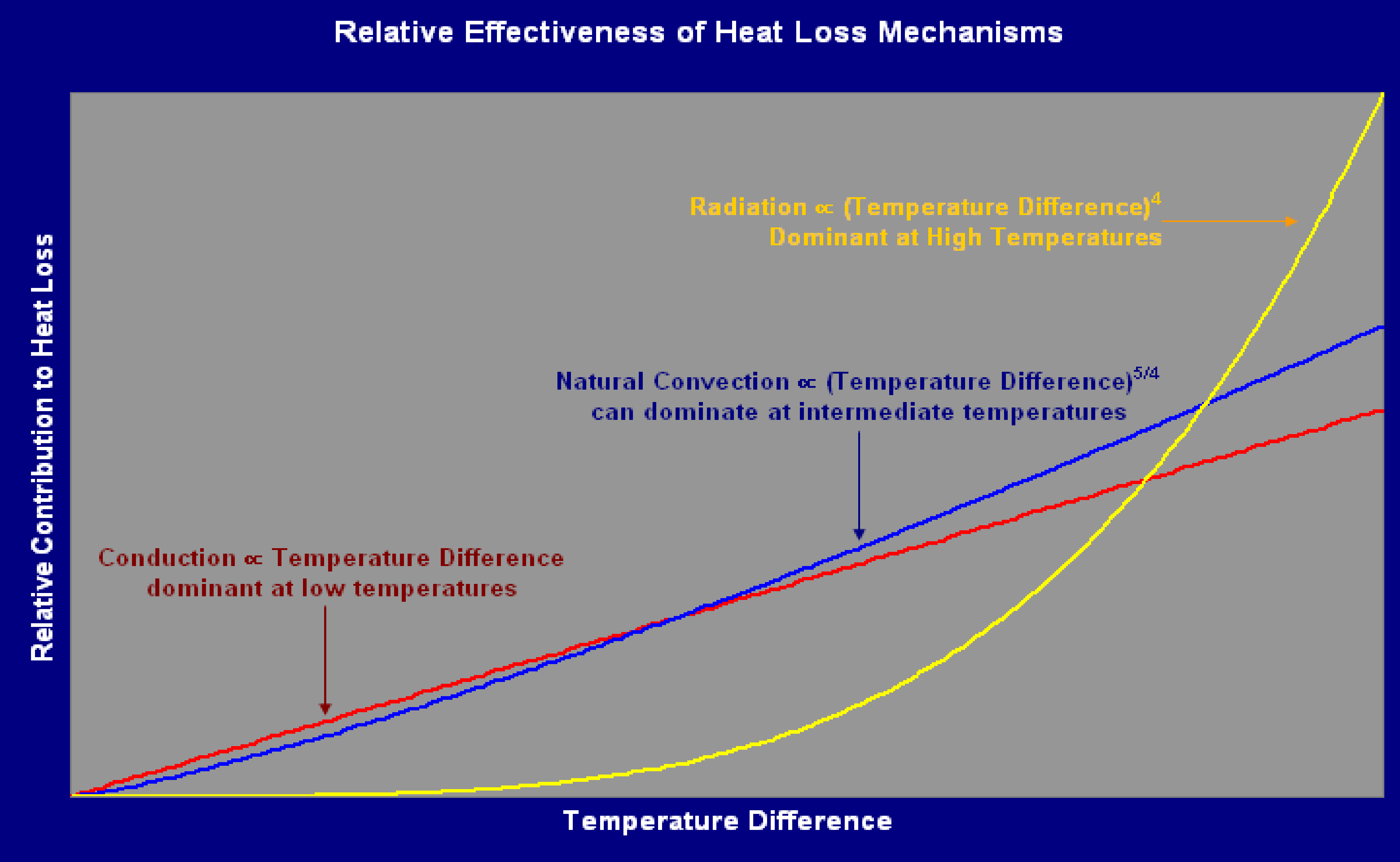
Convection Physically Moves the Hot Fluid to a Colder Place

- **Here's Why -** When heat is input to a material too fast for that material to conduct it away to surrounding material, that material will retain the excess heat, expand, so that its density drops. If there is cooler denser neighboring fluid, it will be heavier and displace the lighter, hotter, expanded material, *i.e.* force upward, that hotter lower density fluid.
- **Convection requires Gravity (real or simulated)!** A fact not nearly stressed enough in the literature.
- **Convection can only happen in fluids:** liquids or gases

Here, heating from below is strong, initiating convection



With higher temperature difference between source and sink, radiation (yellow) comes to dominate



These Rules Usually Hold…

- Within a medium (a gas, liquid, solid)…
- CONDUCTION usually dominates when temperature gradients are low
- CONVECTION usually dominates (in fluids only) when temperature gradients are higher
- RADIATION will dominate if the temperature gradient gets steep enough
- The lower the density of the medium, the sooner will radiation come to dominate heat transfer

What This Means for The Greenhouse Effect

- For climate, the upshot of all this physics is explaining why the surface temperature MUST go up when you add more Greenhouse gases to the atmosphere, so lets explain that as clearly as I can…

Whether it’s Convection, Conduction, or Radiation, This Basic Principle Applies…

- If you add **thermal resistance R** to the medium the heat is moving through, you are clearly impeding that hea transfer.
- But the heat flow IN from the sun MUST be matched by the heat flow OUT from the Earth, in order for the Earth to keep the same temperature.
- So something’s gotta give…

Let’s simpify and combine the different heat transfer modes into a more general equation

- $Q = (1/R) * (T_{surface} – T_{space})^{p}$
- Where **Q** is the heat flow per square foot of atmosphere, out to space
- **R** is the “thermal resistance” of the atmosphere. It’s 1/(conductivity) per foot of depth of the atmosphere
- **p** is a power. p=1 for conduction, p is about 5/4 for convection, and p=4 for radiation. Going through the atmosphere includes some of all 3. But the point is that all are <u>positive</u> powers.

Now, Q (heat) comes in from the Sun and is a constant

- And so, if we raise thermal resistance **R** to the atmosphere through added Greenhouse gases, then the first term in our equation (**1/R**) gets <u>smaller</u>
- The only way **Q** can stay the same, is then for the second term $(T_{surface} - T_{space})^p$ to get <u>bigger</u>
- But how? T_{space} is already at ~absolute 0
- So the <u>only</u> way to raise this second term is to raise $T_{surface}$, and that's what Mother Nature's physics does. **Our climate MUST get hotter if we add GHG's to our atmosphere.**

Key Points: K20 – Temperature and Heat Transfer

- Conduction: Particles hitting particles.
- Convection: Hot, bouyant material forced upward by denser, heavier falling surrounding material.
- Convection requires Gravity to happen at all.
- Radiation: Photons carry the heat, goes up as temperature to the 4th power. Works best in a vacuum.
- Given a mass getting hotter & hotter, radiation comes eventually to dominate heat transfer to its surroundings.
- All 3 mechanisms are important within atmospheres or fluids.
- "R value" is inverse of conductivity, although it's a more general term that can apply for all heat transfer modes.
- The higher the "R value" of a medium, the higher the temperature gradient must be to force a given amount of heat across the medium from one side to the other.
- **Therefore, increase the "R value" of an atmosphere, you force the surface temperature to be higher to achieve that higher temperature gradient.**
- As you steepen temperature gradient, first conduction, then convection, and finally radiation, will dominate heat transfer