Mechanisms of Heat Transfer

You’re getting warmer…
Heat and temperature are among the most misunderstood concepts in science. Temperature is a physical state, based on the molecular activity of an object. If you cut an object in half, each half will have the same temperature. Heat is a transfer of energy, which might change the state of temperature. Heat can be transferred without a change in temperature during a phase change (latent heat). There is no such concept as the amount of heat in an object – heat is an energy transfer.
Heat Transfer

• Heat is a transfer of energy from one object to another due to a difference in temperature
• Temperature is a measure of the molecular energy in an object
• Heat always flows from an object of higher temp ($T_H$) to one of lower temp ($T_L$)
• We are often interested in the rate at which this heat transfer takes place
Three types of heat transfer

- Conduction
- Convection
- Radiation
1.0 Conduction

- Molecules are in constant motion, their speed is proportionate to the temperature of the object
- When two objects come in contact, their surface molecules will transfer momentum
- An aluminum pot will conduct heat from a glass stove-top
1.1 Thermal Conductivity

- Why do tile or cement floors feel cooler than wood or carpet?
- The ability to transfer heat is an intrinsic property of a substance
- Metals are good heat conductors due to the free electrons available
- Heat transfer is energy per unit time = power
1.2 Conductive Transfer

• For two objects at $T_H$ and the other at $T_L$, connected by a rod of uniform material

\[ P = kA(T_H - T_L)/L \]

Where $k$ is the thermal conductivity of the rod, $A$ is the cross-sectional area, and $L$ is the length of the rod

• Home owners are concerned with the “R-value” of their insulation

\[ R = L/k \]

Don’t confuse this $k$ with $k_B$ (the Boltzmann constant)
1.3 Impact of k

- If left alone for sufficient time, both objects will come to thermal equilibrium.
- The smaller the value of k, the slower the heat transfer.
- Home insulation strives to maximize this transfer time (high R-value), allowing for a temperature gradient to exist longer.
2.0 Convection

- A fluid’s density will change when its temperature changes (through conduction)
- This density change can create movement within the fluid
- Warmer fluid is usually less dense, and will rise
- Cooler fluid will rush in to take the place of the rising, warmer fluid
- This mixing is called convection
2.1 Types of Convection

- The previous slide describes the process of \textit{free or natural convection}.
- Using a pump or fan to assist in the mixing process is called \textit{forced convection}.
- The daily weather is determined mostly by natural convection in the troposphere and the oceans.
2.2 No equations (hoorah!)

- There is no simple equation to describe convection. Here are some general statements about convection
  - Heat transfer is proportional to surface area and depth of the fluid
  - Heat transfer due to convection will depend on the viscosity of the fluid
2.3 Convection in the Atmosphere

- Mixing of the atmosphere *within* the troposphere is mostly convection
  - Sea breeze: land warms faster, air over land rises, air from over the sea comes in

- Mechanism for energy transfer *between* atmospheric layers is not well understood
  - If all of the atmosphere were mixing in a convective fashion, there wouldn’t be layers!
3.0 Radiation

- Objects tend to absorb electromagnetic waves from their surroundings.
- An ideal absorber is called a blackbody, an ideal reflector is called a whitebody.
- Objects tend to radiate electromagnetic waves as efficiently as they absorb them.
- The transfer of energy through the emission of EM waves is called radiation.
3.1 Blackbody radiation

- The rate of energy radiation is related to an object’s surface area $A$ and the nature of the surface, called emissivity, $e$
- The Stefan-Boltzmann Law for heat transfer is $P = Ae\sigma T^4$
  - Don’t forget that heat transfer = energy per unit time = power
- $\sigma$ is the Stefan-Boltzmann constant, which is equal to $5.67 \times 10^{-8}$ $\text{W/(m}^2\text{K}^4\text{)}$
3.1.1 Spectral output

- The radiated EM waves from a blackbody are spread over the EM spectrum.
- Early classical physics (Rayleigh-Jeans Law) predicted that radiation would increase as wavelength decreased, which was not observed.
- This was called the ultraviolet catastrophe.
3.1.2 Enter Quantum

- The only way to resolve the ultraviolet catastrophe was to consider that energy is quantized – released in discrete packets called photons.
- Max Planck and Albert Einstein developed the foundations of the quantum theory of electromagnetic radiation.
3.1.2.1 EM Radiation is Discrete

- Electromagnetic radiation then takes on the form $E = h \cdot f$
- Planck's constant, $h$, has a value of $h = 6.626 \times 10^{-34}$ J·s
- Wave relationship still applies: $f = c/\lambda$

- A specific wavelength corresponds to a finite amount of energy
- Longer waves have less energy
3.1.3 Planck and Wien

- Planck’s Law of blackbody radiation provided a fit to observed spectra:
  \[ I(\nu, T) = 2\ h\nu^3c^{-2}\frac{1}{(e^{\frac{h\nu}{k_B T}} - 1)} \]
  \( k_B \) is the Boltzmann constant = 1.38 x 10^{-23} J/K

- Wien’s displacement law gives a value for the peak wavelength at a specific blackbody temperature:
  \[ T \cdot \lambda_{max} = 2.898 \times 10^6 \text{ nm}\cdot\text{K} \]
3.1.4 Blackbody spectra
Terrestrial Absorption & Re-radiation

Image created by Robert A. Rohde / Global Warming Art

Red represents incoming solar radiation

Blue represents outgoing earth re-radiation
Energy Balance

- The incoming solar radiation has a spectral content $\sim$ 5800 K blackbody.
- The outgoing earth re-radiation has a spectral content $\sim$ 250 K blackbody.
- This “spectral shift” can have dire consequences if we introduce molecules into the atmosphere which absorb those longer wavelengths (lower frequencies).
3.1.4.1 The sun and earth

- Notice the yellow line (~ 5800 K)
  - This is our sun’s blackbody temperature
  - The dominant radiation is in the visible part of the EM spectrum
- Notice the red line (300 K)
  - This is approximately our earth’s re-radiated spectrum (actually, closer to 250 K), where infrared is dominant
3.1.5 Radio temperature

- Looking at Planck’s law, if $hv << kT$, you can use the Rayleigh-Jeans approximation
  
  $I(\nu,T) \approx 2\ \nu^2 k_B T/c^2$

- The classical curves closely match the quantum mechanical view at radio frequencies

- Radio astronomers equate the energy coming from a radio source with a temperature

- NOTE: The object is not necessarily a blackbody at that temperature! Scientists would use other spectral information to determine the nature of the radio source.
Atmospheric behavior

Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).

Visible light observable from Earth, with some atmospheric distortion.

Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio waves observable from Earth.

Long-wavelength radio waves blocked.

Image courtesy NASA
Photodissociation

- Occurs when a photon strikes a molecule with sufficient energy to break the intermolecular bonds
- $\text{O}_2 + hf \rightarrow \text{O} + \text{O}$
- At some point, all of the energy at that wavelength will be absorbed, so none will reach the surface
Photoionization

- Occurs when a photon strikes an atom with sufficient energy to dislodge an electron
- $H + hf \rightarrow H^+ + e^-$
- This energy is Extreme UV
- Almost all of the energy at this wavelength is absorbed by earth’s atmosphere
Discrete Absorption

- Occurs when a photon of specific energy bumps an electron into a higher energy state
  - Called “exciting” an atom or molecule
- Not enough energy to ionize or dissociate
Atmospheric Chemical Regimes

- The interaction of the atmospheric constituents with the incoming EM waves is the reason the atmosphere forms distinct layers.
- Different chemical and physical processes dominate each layer.
3.2 Radiation and Absorption

- If an object is not at the same temperature as its surroundings \((T_s)\), there will be a net gain or loss of radiation

\[
P_{\text{net}} = A\varepsilon\sigma T^4 - A\varepsilon\sigma T_s^4 = A\varepsilon\sigma(T^4 - T_s^4)
\]

- A positive \(P_{\text{net}}\) implies a net transfer of energy out of the body (loss)

- Note that as in other forms of heat transfer, it is the temperature difference which matters
3.3 So that’s how it works!

- Thomas Dewar lined a glass bottle with silver, a near-perfect reflector.
- He then suspended that in another glass bottle, surrounded by a vacuum, virtually eliminating conduction and convection.
- You know this as a Thermos® bottle, which keeps hot things hot, and cold things cold, by inhibiting the transfer of heat.