Thermal Energy Transfer
and
Climate

Thermal Energy Transfer

- Heat can be transferred from place to place by three distinct methods
  - Conduction
  - Convection
  - Radiation

Conduction

- Carried out by molecular collisions
- As one end of an object is heated, the molecules there move faster and faster
- The moving molecules collide with their neighbors transferring kinetic energy
- These molecules now collide and transfer kinetic energy farther along the object

- Heat conduction only takes place if there is a difference in temperature
- The rate of heat flow through the substance is proportional to the temperature difference

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

A = cross-sectional area of the object
L = length of the object
k = thermal conductivity

Convection

- Heat flows by the mass movement of molecules from one place to another
- As water is heated on a stove, the water near the bottom heats up and expands
- The hotter water is less dense and rises to the top
- The cooler water at the top is pushed down forming a convection current

- Convection currents can also be forced to occur
  - Air is heated and blown into a room with a fan

Radiation

- Heat transfer that occurs without any medium
- The Sun transfers heat energy though (mostly) empty space to the earth
- The warmth from a fireplace is radiant heat
  - Most of the air heated by convection goes up the chimney and is "wasted"

Blackbody Radiation

Do not all fix'd Bodies, when heated beyond a certain degree, emit Light and shine; and is not this Emission perform'd by the vibrating motion of its parts?

Isaac Newton, Opticks, published 1704.

How do heated bodies radiate?

- At the turn of the century (1900) the idea was that when a body was heated, the consequent vibrations on a molecular and atomic scale inevitably induced charge oscillations that would radiate, presumably giving off the heat and light observed.
- Currently the radiation is explained as standing waves with the probability of modes predicted by quantum mechanics

How is radiation absorbed?

- If radiation is emitted, then it must be absorbed as well
- Glass does not appear to absorb anything, yet it will heat up
  - The same it true for shiny metals
- Dark colored compounds like dirt almost completely absorb light and heat and heat up quickly

- The full explanation requires quantum mechanics, but generally…
  - The electrons in the atoms of non-metals like glass are tightly bound and can only oscillate at certain frequencies
  - If the frequency of the radiation is equal to one of these frequencies (think of resonance) then the radiation is absorbed, otherwise it just passes through

  - In metals, the electrons are free and can oscillate at any frequency
  - This means that the reflected radiation is really just the absorbed radiation being reradiated
  - For dark materials, there are some free electrons that can oscillate (and thus absorb all frequencies) but they bump into things and release their energy as infrared radiation (heat)

Relating Absorption & Emission

- A body emits radiation at a given temperature and frequency exactly as well as it absorbs the same radiation
- A "blackbody" is an idealized body which is a perfect absorber, and therefore also (from the above argument) a perfect emitter
  - It absorbs and emits ALL frequencies of electromagnetic radiation equally well

Stefan-Boltzmann Equation

- Kirchoff (1859) proposed a way to test the "blackbody" theory
  - A small hole placed in the side of a box with the insides painted black is about as good as you can get for an absorber
  - The radiation enters, bounces around, and has a very small probability of getting out

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- Stefan (1879) experimentally showed how total radiated power varied with temperature
- Boltzmann (1884) theoretically derived Stefan's result
- The Stefan-Boltzmann equation:

$$P = \sigma A T^4$$

A = area
σ =the Stefan-Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4})

- For objects that are not ideal blackbodies (everything) an emissivity value, e, is included (e = 1 for ideal blackbody)

$$P = e\sigma A T^4$$

- Emissivity of various surfaces

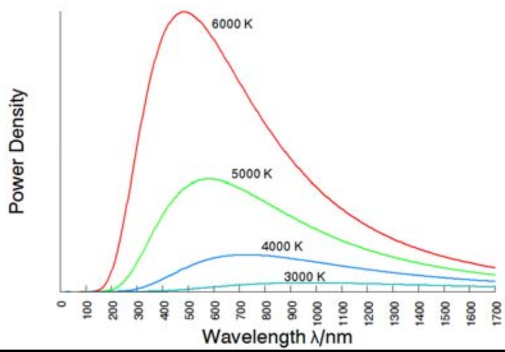
Surface	Emissivity
Ocean water	0.8
Ice	0.1
Dry land	0.7
Land with vegetation	0.6

Wien's Displacement Law

- The energy of a body is electromagnetic radiation distributed over an infinite range of wavelengths
- Most of the energy is radiated at a specific wavelength, λ_{max}, that is determined by the temperature of the body

$$\lambda_{\max} = \frac{2.90 \times 10^{-3}}{T}$$

Blackbody Emission Spectra



Intensity of the Sun on Earth

- The amount of light reaching the top of the earth's atmosphere from the sun is calculated using the inverse square law

$$I = \frac{P}{4\pi d^2}$$

P is the total power emitted by the sun
d is the distance from the sun to the earth

- Using the currently accepted value of $3.9\text{x}10^{26}$ W for the total sun's power and a mean sun-earth distance of $1.5\text{x}10^{11}$m, we can calculate an intensity of ~1400 Wm^{-2}
- This value is called the solar constant
  - Currently accepted value is 1368 Wm^{-2}

- A number of assumptions and approximations are used in the calculation:
  - the surface receiving the radiation is perpendicular to the radiation
    - The light is almost never perpendicular at the earth due to rotation of the earth and the tilt of the earth's axis
  - the surface receiving the radiation is at a mean Sun-Earth distance
    - The earth revolves around the sun in an ellipse
  - radiation emission from the Sun remains constant
    - The radiation emission of the varies with solar cycles

Albedo

- The ratio of the power of radiation reflected or scattered from the body to the total power incident on the body

$$\text{albedo} = \frac{\text{total scattered power}}{\text{total incident power}}$$

- Albedo is a dimensionless number
- The larger the albedo, the more radiation is reflected
  - Snow = 0.85
  - Charcoal = 0.04
  - Desert = 0.3 – 0.4
  - Forests = 0.1
  - Annual global average = 0.3
- Earth's albedo varies daily and is dependent on the seasons and latitude

The Greenhouse Effect

- The solar radiation reaching the earth is mainly radiation in the visible spectrum
- ~30% of this radiation is reflected back into space the rest warms the earth and the atmosphere
- The earth radiates heat back at infrared wavelengths which are absorbed by various gases in the atmosphere

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- The gases that absorb infrared radiation are called greenhouse gases
- If it were not for this greenhouse effect, the earth's average temperature would be ~32°C colder than it is

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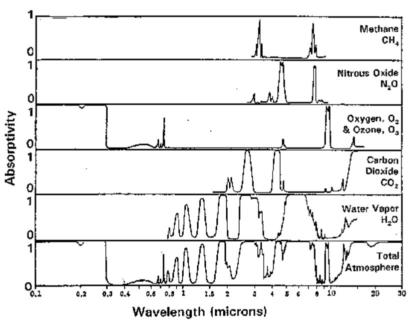
- Therefore, the greenhouse effect may be described as the warming of the earth caused by infrared radiation, emitted by the earth's surface, which is absorbed by various gases in the earth's atmosphere and is then partly re-radiated towards the surface.

Greenhouse Gases

- Water vapor (H_2O)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Carbon dioxide (CO_2)

ABSORPTION SPECTRA FOR MAJOR NATURAL GREENHOUSE GASES IN THE EARTH'S ATMOSPHERE



[After J. N. Howard, 1959: *Proc. I.R.E. 47*, 1459; and R. M. Goody and G. D. Robinson, 1951: *Quart. J. Roy. Meteorol. Soc. 77*, 153]

Solar Radiation