NATS 101
Section 13: Lecture 5

Radiation
What causes your hand to feel warm when you place it near the pot?

NOT conduction or convection. Why?

Therefore, there must be an mechanism of heat transfer which DOES NOT require the presence of molecules.
Radiation: Energy propagated by electromagnetic waves, which travel at the speed of light (~3.0 x 10^8 m s^{-1}) in a vacuum. The electromagnetic waves are caused by acceleration of charges within atoms and molecules.

All matter that has a temperature above absolute zero emits some kind of radiation.
Radiation and photons

Radiation can be thought of as a photon, or discrete packet of electromagnetic radiation. The energy of the photon corresponds to the type of radiation.

<table>
<thead>
<tr>
<th>TYPE OF RADIATION</th>
<th>RELATIVE WAVELENGTH</th>
<th>TYPICAL WAVELENGTH (meters)</th>
<th>ENERGY CARRIED PER WAVE OR PHOTON</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM radio waves</td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Television waves</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Microwaves</td>
<td></td>
<td>$10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>Infrared waves</td>
<td></td>
<td>$10^{-6}$</td>
<td></td>
</tr>
<tr>
<td>Visible light</td>
<td></td>
<td>$5 \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>Ultraviolet waves</td>
<td></td>
<td>$10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>X rays</td>
<td></td>
<td>$10^{-9}$</td>
<td></td>
</tr>
</tbody>
</table>

Longer wavelengths $\rightarrow$ low energy

Shorter wavelengths $\rightarrow$ high energy
High energy radiation certainly can be dangerous!

Why is high energy radiation hazardous to life?
Much of the technology of our present age has developed because of our understanding of the nature of radiation during the past century!
Note that for electromagnetic waves:

\[ c = f\lambda \]

\textit{Speed of light} = \textit{frequency} \times \textit{wavelength}

\( c \) = speed of light

\( f \) = frequency (s\(^{-1}\) or Hertz)

\( \lambda \) = wavelength (m)
Visible Spectrum through a Prism

Visible part of the spectrum: 0.7 to 0.4 µm

1 µm = 10^{-6} m

Longer wavelength 0.7 µm  
Shorter wavelength 0.4 µm
Rainbows occur as a result of sunlight being reflected within raindrops.

Each wavelength of the visible spectrum is reflected at a slightly different angle.
Human eyes detect radiation in the visible part of the spectrum: (0.4 – 0.7 μm).

Typically, this radiation is reflected off objects, not generated by them.
Our touch is designed to sense the infrared part of the spectrum (around 5 – 15 µm) and gives us our sense of “hot” and “cold.”
What if we could “see” in infrared?

This is what a house on a cold winter day might look like...

Hot areas appear in red and orange.

Cold areas appear in blue and purple.

Areas in between relatively hot and cold appear green.
Planck Function

The intensity of radiation as it relates to the frequency (or wavelength) and temperature of a body was first described by Max Planck in 1900

\[ I(f, T) = \frac{2hf^3}{c^2} \left( \frac{1}{e^{hf/kT}} - 1 \right) \]

**Variables**

- \( I(f, T) \) = Intensity of radiation
- \( f \) = frequency
- \( T \) = Temperature

**Constants**

- \( h \) = Planck’s constant
- \( k \) = Boltzmann’s constant
- \( e \) = natural logarithm
- \( c \) = speed of light
Planck Function Characteristics

Peak radiation intensity is *inversely* related to the wavelength and temperature.

Greater intensity with __________ wavelength and __________ temperature.

---

Figure from *Wikipedia*
Wien’s Displacement Law

Gives an expression for the wavelength at which peak radiation emission occurs:

\[ \lambda_{\text{max}} = \frac{2897 \, \mu\text{m K}}{T} \]

Reflects the characteristics of the Planck curve we just observed:

The wavelength of maximum radiation emission is inversely proportional to an object’s temperature.
Total Radiant Energy per unit area: Stefan-Boltzmann Law

The total radiant energy per unit area \( E \) is obtained by integration (or computation of the area under the curve) the Planck function \( l \) over all wavelengths over a half sphere.

\[
E = \int_0^\infty \int_0^{2\pi} \int_0^{\pi/2} l(f, T)(\cos \theta)(\sin \theta)d\theta d\phi df
\]

Solution:

\[
E = \sigma T^4
\]

\( \sigma = \text{Stefan-Boltzmann constant} \)

\( \sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \)
Total Radiant Energy per unit area:
Stefan-Boltzmann Law

Main point I want you to remember...

The total radiant energy is proportional to the AREA UNDER the Planck function curve.

More area → more radiant energy!
Total Radiant Energy per unit area: Stefan-Boltzmann Law

\[ E = \sigma T^4 \]

Relatively SMALL changes in temperature cause LARGE changes in the total radiant energy.

How does energy change with a doubling of temperature?
NOTE: More shaded area underneath the curve

1.

2.
Solar and Terrestrial Radiation

The Planck curves based on the emission temperatures of the Sun and Earth define the range of solar and terrestrial radiation.

By application of Wein’s law, we can obtain $\lambda_{\text{max}}$. This is shown in the textbook.

**SOLAR**

$\lambda_{\text{max}} = 0.5 \, \mu\text{m}$

**TERRESTRIAL**

$\lambda_{\text{max}} = 10 \, \mu\text{m}$
How much more radiant energy per unit area does the sun emit compared to the Earth?

*Answer: About 160,000 times more!*

*How can we use the concepts we’ve discussed so far to determine that answer?*
Total radiant energy per unit area: Sun vs. Earth

Sun: \( T = 5800 \) K

\[
E_{\text{Sun}} = \sigma T_{\text{Sun}}^4
\]

\[
E_{\text{Sun}} = (5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})(5.8 \times 10^3 \text{ K})^4
\]

\[
E_{\text{Sun}} = 6.41 \times 10^7 \text{ W m}^{-2}
\]

Earth: \( T = 288 \) K

\[
\frac{E_{\text{Sun}}}{E_{\text{Earth}}} = 1.64 \times 10^5 \approx 160,000
\]

Do this part on your own and confirm the answer from the ratio
Keep in mind that we’re talking about the total radiant energy PER UNIT AREA.

Accounting for the area of the Earth and the Sun, the Sun emits almost 2 billion times the amount of energy as the Earth!
Not all stars are created equal in the universe!

Source: Faulkes Telescope Educational Guide  
http://www.le.ac.uk/ph/faulkes/web/stars/r_st_evolution.html
Summary of Three Modes of Heat Transfer

CONDUCTION: Molecule to molecule within a substance

CONVECTION: Mass movement of a fluid or gas

RADIATION: Electromagnetic waves
Summary of Lecture 5

The three modes of heat transfer are conduction, convection, and radiation. Radiation is energy propagated by electromagnetic waves and is emitted by all objects so long as they have a temperature.

The type of radiation an object emits is dependent on its temperature. The smaller the wavelength of radiation, the greater the energy and the higher the temperature. The entire range of radiation types is given by the EM spectrum.

The total radiant energy emitted by an object is described by the Stefan-Boltzmann law.

The wavelength of maximum radiation emission is described by Wien’s law.

Solar radiation, or shortwave radiation, is that which comes from the sun and is most intense in the visible part of the spectrum.

Terrestrial radiation, or longwave radiation, is that which comes from the Earth and is most intense in the infrared part of the spectrum.
Reading Assignment and Review Questions

Ahrens, Chapter 2, pp. 40-51 (8th ed.)
pp. 40-52 (9th ed.)

Chapter 2 Questions

Questions for Review: 4c, 7, 8, 9, 10

Questions for Thought: 6

Problems and Exercises: 2, 3