"From a long view of the history of mankind ... the most significant event of the 19th century will be judged as Maxwell's discovery of the laws of electrodynamics." Richard Feynman, *American physicist (1918-1988)*

"This change in the conception of reality is the most profound and the most fruitful that physics has experienced since the time of Newton."

Referring to Maxwell's contributions to physics.

Albert Einstein, *German-American physicist (1879-1955)*

"He achieved greatness unequalled."

Max Planck, *German physicist (1858- 1947)*

James Clerk Maxwell (1831-1879), aged 24.
Photo: Trinity College, University of Cambridge.

Current Assignments ...

For today:

- Read Sections 9.3 - 9.7

For Lecture 11:

- Read Section 9.8

Office hours:
3-4 Tuesdays
& Thursdays

Suggested Conceptual Exercises:

- Chapter 9: 1,3,5,7,9,11,13,19,21,23,29,31,33

Homework #2

- Due 11:00 AM, Thursday, February 14

Writing Assignment #1

- Due 11:00 AM, Thursday, February 28

Tutorials

- Tutorial #4 this week

Review of Lecture 9

Textbook, Sections 8.6, 9.1, 9.2

- Electromagnetism
- Waves
- Interference of waves

Plan for Lecture 10

Textbook, Sections 9.3 - 9.7

- Light: particle or wave?
- The double slit experiment
- Electromagnetic wave theory of light
- Electromagnetic spectrum
- Solar radiation
- Blackbodies

From Lecture 9:
Wave Interference in 2D

Textbook Figure 9.11

Textbook Figure 9.12

What Is Light: Particle or Wave?

- Some things are sources of light, such as light bulbs and the sun.
- Everything else, such as the moon and our furniture, we see by reflection.
- So, what enters your eyes when you see light? In particular, is it a particle or a wave?
- One way to tell is if we can get light to exhibit interference.
  - → We need two sources of light that have identical vibrations. One way is to have a single light go through a screen with two slits.

Young's Double Slit Experiment

- First performed by Thomas Young in 1801.
- Goal was to answer the question of whether light was made of particles (Newton's "corpuscular" theory), or of waves travelling through some ether, just as sound waves travel in air.

Textbook Figure 9.16

Young’s Double Slit Experiment

What happened?

Young's two-slit experiment with laser light

- http://www.colorado.edu/physics/2000/applets/twoslitsa.html

  The resulting interference pattern supported the wave theory of light.

  Light is a wave.*

Textbook Figure 9.17

***for now, stay tuned!**

Double Slit Experiment

PhET interactive animation

- http://phet.colorado.edu/en/simulation/wave-interference

Interactive - vary wavelength and separation

- http://dev.physicslab.org/asp/applets/doubleslit/default.asp

Interactive ripple tank animation

- http://www.falstad.com/ripple/ex-2slit.html

Try these animations at home

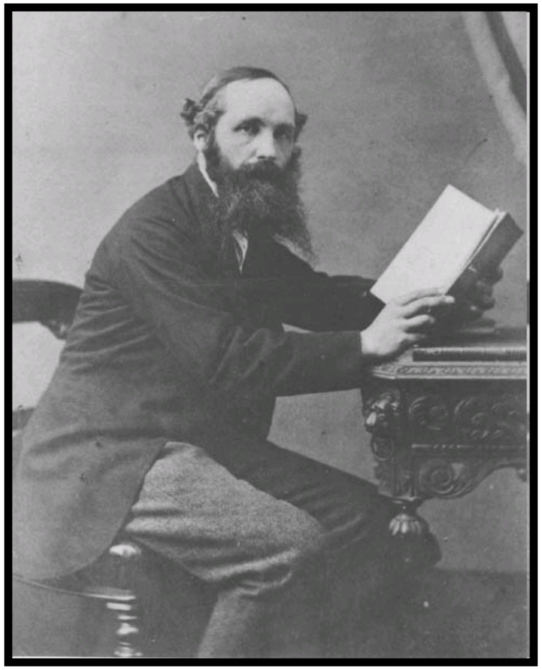
The EM Wave Theory of Light - 1

- Imagine a charged object, like a balloon, a pith ball, or a comb.
- It exerts an electric force on other charged objects, and when moved, it exerts a magnetic force on magnets.
- The magnitude of the force depends on the distance between the objects.
- Imagine shaking the balloon/pith ball/comb.
  - $\rightarrow$ How long does it take for the other charged object or the magnet to react?

The EM Wave Theory of Light - 2

- Shaking changes the electric and magnetic fields created by the moving charge.
- Does this change appear everywhere instantaneously or does it take some finite time?
- This question was studied by Maxwell, who thought that the equations of electromagnetism should treat electric and magnetic fields similarly.

http://www.clerkmaxwellfoundation.org/



Two charged particles are placed a short distance apart in a vacuum.

The electric force exerted by one on the other:

(A) Cannot be felt due to the vacuum.

(B) Is transmitted instantaneously.

(C) Is transmitted at the speed of light.

(D) Is due to gravity.

(E) Is due to friction.

Let's see why ...

Maxwell's Equations

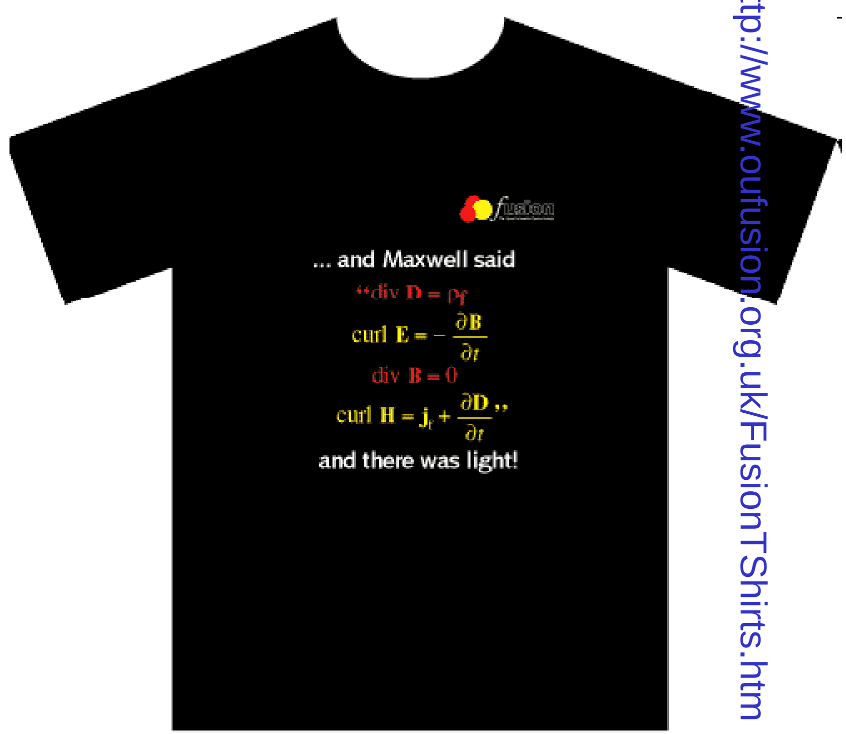
Maxwell's electromagnetic field theory can be thought of as four relationships:

(1) the electric force law

(2) the magnetic force law

(3) Faraday's law: a changing magnetic field creates an electric field

(4) Maxwell's contribution: a changing electric field creates a magnetic field



http://www.oufusion.org.uk/FusionTShirts.htm

Predictions of Maxwell's Equations

Maxwell's Equations predict:

- The existence of electromagnetic waves.
  - → An oscillating electric charge creates an electromagnetic wave, which consists of changing electric and magnetic fields.
- That EM forces take time to propagate, rather than changing at all points simultaneously.
- The speed of propagation of these waves – 300,000 km/s.
  - → This had already been measured as the speed of light – so is light an electromagnetic wave?

Generating Electromagnetic Waves

Figure 9.22
Shaking a charged object will make other charged objects shake in response.

Textbook Figure 9.24

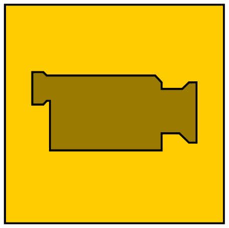
Textbook Figure 9.22

Figure 9.24 Shaking a charged object will make it send out an EM wave in all directions. This wave is a disturbance in the EM field of the charged object.

Fields of Oscillating Charges

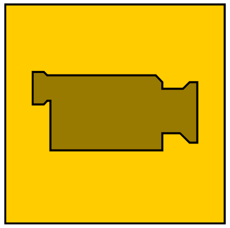
The electric field of an oscillating charge:

- http://www.upscale.utoronto.ca/GeneralInterest/Harrison/Flash/EM/LightWave/Wave.html



The electric and magnetic fields generated by an oscillating electric charge:

- http://www.upscale.utoronto.ca/PVB/Harrison/Flash/EM/EMWave/EMWave.html



The EM Wave Theory of Light - 3

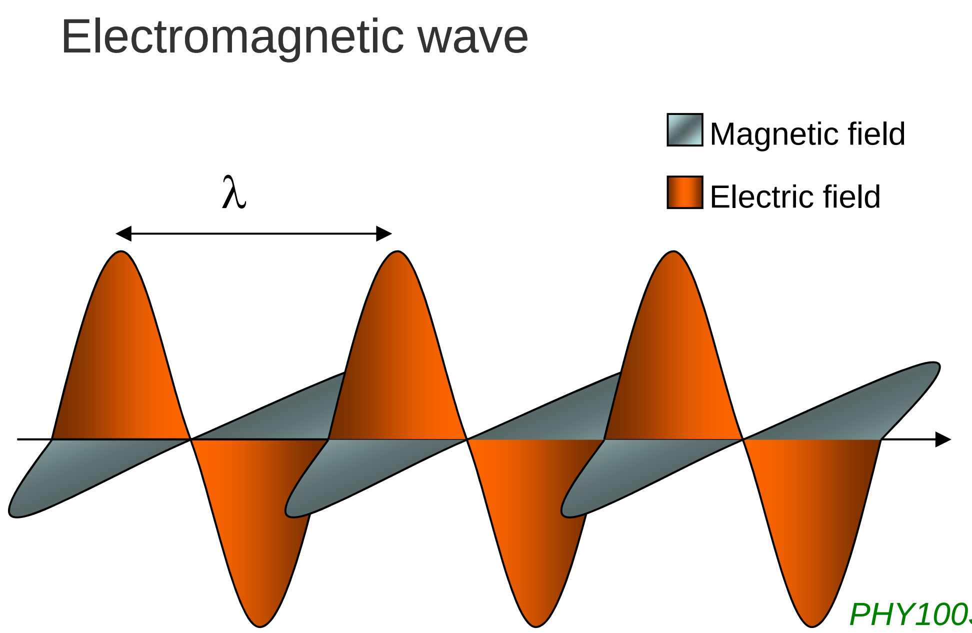
Maxwell (1864), before the Royal Society of London in 'A Dynamic Theory of the Electro-Magnetic Field', said:

"We have strong reason to conclude that light itself - including radiant heat and other radiation, if any - is an electromagnetic disturbance in the form of waves propagated through the electro-magnetic field according to electro-magnetic laws."

The existence of EM waves was verified by Heinrich Hertz (1887).

The EM Wave Theory of Light - 4

Every vibrating charged object creates a disturbance (wave) in its own electromagnetic field. This disturbance spreads outward through the field at lightspeed, 300,000 km/s. Light is just an electromagnetic wave.



The Decline of the Newtonian Universe

Key ideas:

- Electromagnetic fields contain energy.
- Scientists postulated the existence of an ether, which permeated everywhere and everything, and which was the medium for electromagnetic waves.
  - → It was later proven that ether does not exist.
  - → Electromagnetic fields propagate in vacuum.
- This vacuum is not entirely empty – it is full of fields!
  - → The beginning of post-Newtonian physics.

The Electromagnetic Spectrum

- Imagine shaking a charged object quickly.
- Does this create an electromagnetic wave?
- What is its frequency?
  Its wavelength?

Textbook Figure 9.24

The Electromagnetic Spectrum

- The frequencies of visible light are around 10^{15} Hz.
- However, electromagnetic waves can have any frequency; different frequency ranges are given different names.
- This range of frequencies is called the <u>electromagnetic spectrum</u>.
- Electromagnetic waves carry <u>radiant energy</u>, and are sometimes called <u>electromagnetic radiation</u>.

The Electromagnetic Spectrum

Textbook Figure 9.27

Regions of the EM Spectrum - 1

Radio waves

- Longest wavelengths, down to about 1 mm
- Include AM, FM, TV, and microwaves
- Many natural processes also create radio waves
- Radio astronomy – using radio telescopes to detect radio waves – is a very active field of research

Regions of the EM Spectrum - 2

Infrared radiation

- Next range, from 1 mm to about 0.001 mm
- Typically caused by the thermal motion of molecules in a substance
- Perceived as heat

Regions of the EM Spectrum - 3

Visible light

- Has wavelengths around 5×10^{-7} m (400-700 nm)
- Created by individual electrons in atoms, as they change from one energy level to another
- The longest wavelengths are perceived as red; shortening the wavelength gives orange, yellow, blue, and violet in a continuous gradation - the rainbow

Regions of the EM Spectrum - 4

Ultraviolet radiation

- The next shortest wavelengths, or higher frequencies
- Also created by changes in atomic electrons, but its energy is higher, making it more dangerous to living cells
- Ultraviolet radiation is a leading cause of skin cancer

Regions of the EM Spectrum - 5

X-rays

- Created by highest-energy electron interactions possible in atoms
- Can destroy living cells, and pose a cancer risk
- Widely used in medicine

  → newer X-ray machines use much less power than older ones, making them safer

Textbook Figure 9.29

Regions of the EM Spectrum - 6

Gamma rays

- Highest-frequency electromagnetic waves
- Produced in nuclear reactions such as fusion and fission
- Can also damage living cells
- Their wavelengths are so short compared to the size of the atom that they only interact with the nucleus, and can penetrate deeply into matter

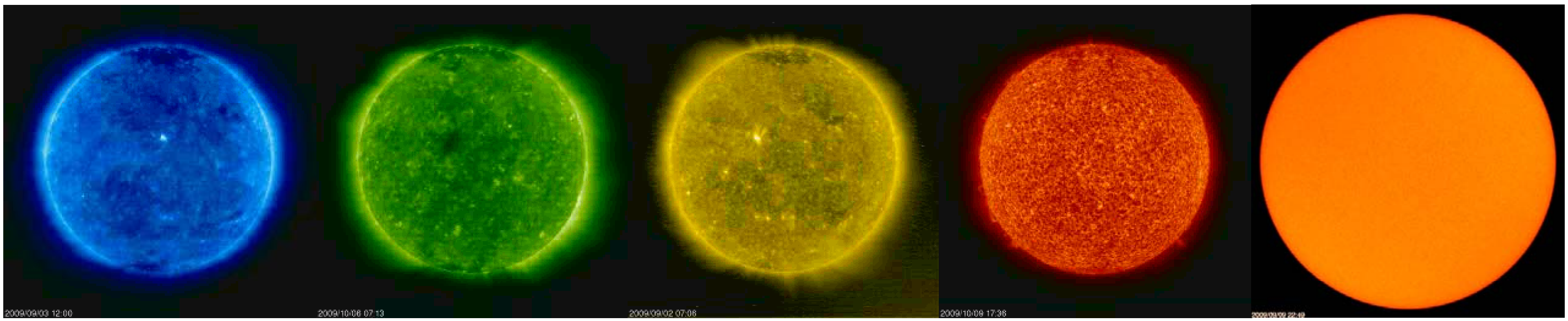
The Solar Spectrum

The sun emits all wavelengths of EM radiation, with the most energy in the visible, ultraviolet, and infrared regions.

Textbook Figure 9.30

SOHO Images of the Sun

- Solar & Heliospheric Observatory (1995 -)
- One month or 48 hours in Sept-Oct 2009
- From http://sohowww.nascom.nasa.gov/



λ = 17.1nm λ = 19.5nm λ = 28.4nm λ = 30.4nm λ = 677nm

1 million degrees

60,000-80,000°

Images taken with the Extreme ultraviolet Imaging Telescope

Michelson Doppler Imager

http://sohowww.nascom.nasa.gov
/data/realtime/soho/soho_fader.html

Blackbodies

- The Sun behaves like a blackbody at a temperature of approximately 6000 degrees.
- A blackbody is a perfect emitter - it emits the maximum possible amount of radiation at each wavelength.
- A blackbody is also a perfect absorber, absorbing at all wavelengths of radiation incident on it. Therefore, it looks black.
- Every object emits radiation, with emissivity:

$$\varepsilon_\lambda \equiv \frac{\text{emitted radiance at } \lambda}{\text{blackbody radiance at } \lambda}$$

The Blackbody Spectrum

http://www.colorado.edu/physics/phet/simulations/blackbody/blackbody.swf

- Blackbody radiation depends on the temperature of the emitting object.
- Humans tend to be warmer than our surroundings. We emit energy (~ 100 Watts for an average adult at rest) in the infrared.
- Although we also absorb infrared radiation from our surroundings, there is a net energy loss – replaced by metabolic processes.

Solar and Terrestrial Radiation

- Solar spectrum
  - → peaks in visible, near 500 nm (or 0.5 microns)
  - → known as <u>shortwave</u> radiation
- Earth's spectrum
  - → peaks in the infrared, near 10 microns (μm)
  - → known as <u>longwave</u> radiation