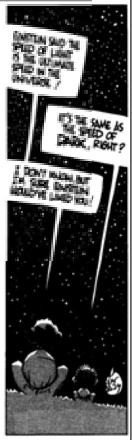
May 9, 2011 Physics 122 Prof. E. F. Redish

- **Theme Music:**
  Matisyahu
  I Will be Light*

  *Thanks to Dan Makover
  For bringing this song to my attention

- **Cartoon:**
  Pat Brady
  Rose is Rose



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Outline

- Quiz 11: Capacitors (using clickers)
- What is light?
  - Unified theory of electromagnetism
  - Maxwell's rainbow
  - Hertz's invisible light
  - But…

5/10/10 Physics 122 2

Model of magnetism (alpha): Magnetic poles

- Magnetism is a third "non-touching" force like gravity and electricity.
- Magnets are made up of "magnetic charges" analogous to electric charges but different. We will call them "magnetic poles" – North and South to distinguish them from Positive and Negative.
- Magnetic materials are made up of N and S just like they have + and - charges. When they are magnetized, the N's and S's separate.

5/10/10 Physics 122 3

Is there "magnetic charge"?

- If you break a magnet in half, both parts are still full (N-S) magnets.
- You can do this all the way down to a single electron and it still holds true (and you can't break a single electron).
- Our "little dipoles" turn out to be electrons.

Model of magnetism (beta): Magnetic dipoles

- No separate magnetic poles have ever been found.
- All matter contains small "magnetic dipoles" – little bar magnets that cannot be broken.
- When magnetic materials are magnetized, the little dipoles are aligned and the forces they exert on each other hold each other in place.
- When they are heated, the little magnets lose their alignment and go random.

Basic Particles

- The fundamental particles making up matter (electrons and protons and neutrons) can be classified by how they behave in response to (and as sources of) gravity, electricity, and magnetism.

	Mass	*Charge*	*Magnetic Moment*
proton	1.67×10^{-27} kg	1.6×10^{-19} C	0.0015 Bohr magnetons
neutron	1.67×10^{-27} kg	0	0.0010 Bohr magnetons
electron	9.1×10^{-31} kg	-1.6×10^{-19} C	9.28 Bohr magnetons

Moving electrons are deflected by a magnet.
Is it because they are little magnets?

Fields

Field	*Source*	*Response*
gravity	mass	mass
electricity	charge	charge
magnetism	moving charge / magnetic dipoles	moving charge / magnetic dipoles

Foothold ideas: Magnetism 1.0

- Magnetic fields are produced by magnets.
- Magnetic fields are felt by magnets and by moving charges.
- Magnetic force law: $\vec{F}_B = q\vec{v}\times\vec{B}$ $\Delta\vec{F} = I\Delta\vec{L}\times\vec{B}$
- Although there are magnetic dipoles (e^-, p^+) there are no separate magnetic poles.

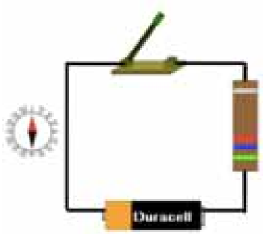
Fie

Note the asymmetry:
So far we have only noted that moving charges *feel* a force from a magnetic field.
Can they create them as well?

Field	*Source*	
gravity	mass	mass
electricity	charge	charge
magnetism	magnetic dipoles	moving charge / magnetic dipoles

5/10/10 Physics 122 **10**

Moving charges create as well as feel magnetic fields



This suggests that currents should attract and repel.

5/10/10 Physics 122 **11**

Foothold ideas: Magnetism 2.0

- Magnetic fields are produced by magnets and by moving charges (currents).
- Magnetic fields are felt by magnets and by moving charges (currents).
- Magnetic force law: $\vec{F}_B = q\vec{v}\times\vec{B}$ $\quad \Delta\vec{F} = I\Delta\vec{L}\times\vec{B}$
- Magnetic field law: $\Delta\vec{B} = k_A \frac{I\Delta\vec{L}\times\hat{r}}{r^2}$
- Although there are magnetic dipoles (e^-, p^+) there are no separate magnetic poles.

5/10/10 Physics 122 **12**

Some surprising results relating E and B

- Again we find an asymmetry:
  If a moving charge feels a magnetic field, does a moving magnet feel an electric field?
- Yes! Furthermore…never mind charges:
  - Changing magnetic fields create electric fields.
  - Changing electric fields create magnetic fields.

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Faraday's Law: A changing magnetic field creates an electric field

And one which, by the way, does *NOT* satisfy the Kirchoff loop rule!

Including magnetism in our treatment of electric currents – generators, transformers, etc. – requires additional foothold principles.

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Faraday's law is immensely enabling

- This allows us to create immensely useful devices
  - Generators (moving magnets to create currents)
  - Transformers (carrying electrical energy across gaps)
  - Lots more

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Fields

Field	*Source*	*Response*
gravity	mass	mass
electricity	charge changing electric fields	charge moving magnets
magnetism	magnetic dipoles changing magnetic fields	moving charge / magnetic dipoles

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Maxwell's Synthesis

- So our electric and magnetic fields seem deeply intertwined.
- In 1865, a Scottish physicist named James Clerk Maxwell created a unified theory of electric and magnetic fields.

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Maxwell's Principles

- *Maxwell 1*: Point charges serve as sources to create electric fields. (Coulomb's Law)
- *Maxwell 2*: There are no point poles that serve as sources to create magnetic fields.
- *Maxwell 3*: Moving electric charges and changing electric fields create magnetic fields.
- *Maxwell 4*: Changing magnetic fields create electric fields.

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A Unified Field Theory

- Maxwell's equations provide the first "Unified Field Theory" – a set of equations that describe two fields (electric and magnetic) and specify the relationship between them.
- These equations turn out to be highly accurate until one gets to distances that are small compared to atomic sizes / energies that are large compared to atomic energies.
- These equations turn out to conflict with Newton's laws with respect how things look to moving observers – and Maxwell's equations turn out to be right and Newton's wrong. This requires us to modify Newton's laws when speeds get near to c. This led directly to Einstein's special theory of relativity.

5/10/10 Physics 122 **19**

A Remarkable Result

- Since in Maxwell's equations electric and magnetic fields can "bootstrap" each other through empty space – with the changing electric field producing a changing magnetic field which produces… we can get fields that change continually and propagate through space.
- The speed of this wave is a combination of the constants obtained through studies of electric and magnetic forces:

$$v = \sqrt{\frac{k_A}{k_C}} = 3 \times 10^8 \ \frac{\text{m}}{\text{s}}$$

5/10/10 Physics 122 **20**

Putting light in its place

- Maxwell's result suggests that light was in fact waves of oscillating electric and magnetic fields.
- It also suggests the intriguing possibility that there might be other kinds of light – different frequencies – that we couldn't see.

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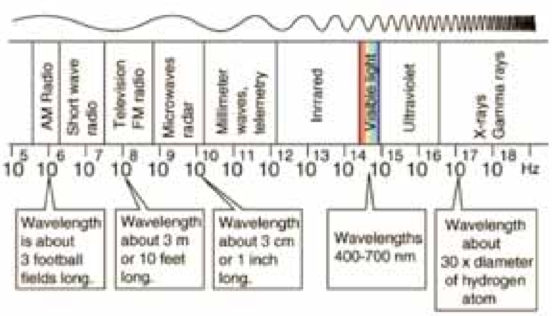
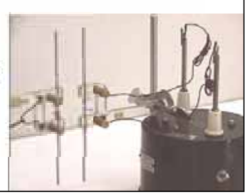
Maxwell's Rainbow



5/10/10 Physics 122 22

Hertz's Invisible Light

- In 1887 Heinrich Hertz demonstrated that Maxwell's prediction – that EM Energy could be transmitted as waves – was correct.
- This experiment was the basis for the invention of radio (and TV, and WiFi,…..)



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All is hunky-dory – Or is it?

- With Maxwell's theory and Hertz's experiment, physicists in 1890 felt they understood almost everything.
  - Motion (Newton's Laws)
  - The basic forces (gravity, electricity, magnetism)
  - The basic character of matter (made of charges)
  - The nature of heat (motion)
  - The nature of light (waves of electric and magnetic fields)

5/10/10 Physics 122 24

Three Questions

- Three important questions at the turn of the 20^{th} century were
  - Maxwell's equations predict a speed of light. Who should measure that speed?
  - How are the charges that make up matter put together?
  - How does matter emit and absorb light (EM waves)?

5/10/10 Physics 122 25

Three Problems

- Considering these issues there were three observations that created "three small clouds on the horizon of physics."
  - 1. Experiments were unable to figure out who should measure light as traveling with speed c. Everybody seemed to get that no matter how they were moving in space. (*Michelson-Morley experiment*)
  - 2. Matter "excited" by a spark gave off light at very specific frequencies. (*spectral lines*)
  - 3. Matter heated gave off light with a mixture of colors that could not be explained. (*thermal radiation*)

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The solution?

- The solution to these three problems led to the physics of the 20^{th} century –
  - Einstein's theory of relativity
  - Quantum physics
- These theories led to great surprises and the knowledge that dominates much of our technology today – transistor, lasers, and our understanding of chemical mechanisms.

5/10/10 Physics 122 27

Photons

- Surprisingly, it turns out that both Newton and Huygens were partly right.
- Light appears to travel in little packets of energy – like particles – but whose energy and momentum are determined by wave properties: $E = hf \quad p = h/\lambda$
- The electric and magnetic field waves determine the probability that the photons will be found in a particular place.

5/10/10 Physics 122 **28**

- http://phys.educ.ksu.edu/vqm/html/doubleslit/index.html

5/10/10 Physics 122 **29**