Ch. 22: Electromagnetic waves.

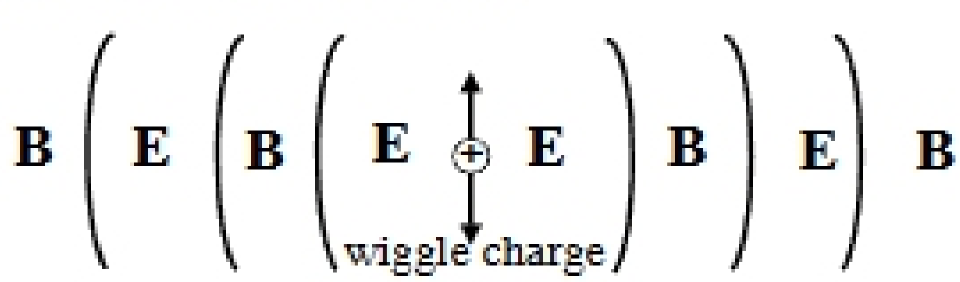
We've seen some of the ideas/discoveries of Ampere, Faraday, and others. So far, **E** & **B** seem different but somehow related. In what is perhaps one of a small handful of truly triumphant intellectual breakthroughs in physics, **James Clerk Maxwell** (a Scot, in the mid 1800's) put it all together and came up with just four equations which described *all* electromagnetic phenomena!

1) **Gauss' Law** : Charges create E, in specific "patterns". E fields superpose. Coulomb's Law is a "special case".
2) The analogue of 1 for B fields (but, there are no *magnetic monopoles*)
3) **Faraday's Law:** Changing B makes E.
4) **Ampere's Law**: Currents make B
"New and Improved": Changing E will also make B.

This last piece was Maxwell's insight. It was not based on experiments (like all the rest). Maxwell argued as a "theorist", arguing from <u>symmetry</u>. (It was only later demonstrated in the lab.)

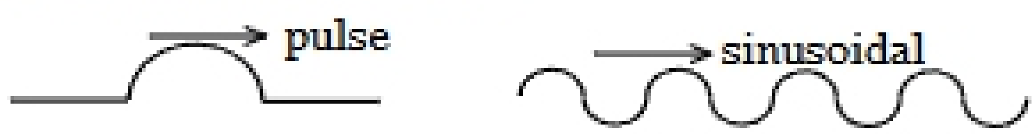
The math of those 4 equations is a little tough (vector calculus is required). There are many consequences, but one in particular is quite remarkable: Imagine shaking a charge "q" up & down. The E-field is thus "shaking" too. Maxwell's big insight was that a changing E induces (creates) a B-field. But this new B-field is itself "shaking", so Faraday's law says this in turn creates a new E-field, which creates a new B, which…

Like wiggling a water molecule, which makes a neighbor wiggle, which makes <u>its</u> neighbor wiggle…= a traveling wave. But here, what exactly is waving? It's nothing *physical*, exactly, it's the E and B fields themselves turning on and off. You need a charge to *start* it, but the wave can them propagate through *empty* space (**vacuum**). You would call this an **"Electromagnetic Wave"** or "EM Wave". People also call this "**EM Radiation**."



Maxwell derived this mathematically. Perhaps he wondered, are there any *examples* of these EM waves in nature? Could we produce and observe such a wave in the lab? If you did, what would it "look" like? How fast would it travel? Giancoli "derives" the answer to this last question, but the math is pretty hard.

Maxwell derived the speed of EM waves himself:
speed = $\sqrt{4\pi k/\mu_0}$ = $1/\sqrt{\varepsilon_0\mu_0}$ .. This is traditionally called "c".
• This formula is independent of the details of the wave.
E.g., you get the same answer whether you have a little "pulse" traveling, or a full sinusoidal wave.



• Recall, the *constant of nature* ε_0=1/(4πk) = 8.85 $*10^{-12}$ [C^2/Nm^2]
Experimentally found with pithballs, cat fur, etc. (Ch.16)

• The other (magnetic) *constant of nature was* μ_0=4π$*10^{-7}$ [T m/A]
Experimentally found with wires, compasses, and currents (Ch. 20)
Both are known, fundamental constants of nature.
Plugging in #'s: $c = 1/\sqrt{\varepsilon_0\mu_0} = 3.00\cdot10^8$ m/s (= 186,000 mi/s)

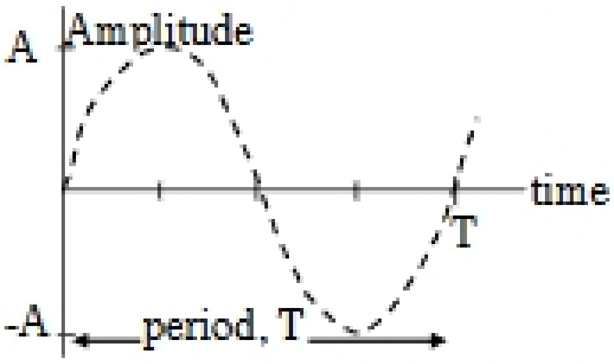
Try to imagine Maxwell's reaction when he came up with this #, because it's very familiar to physicists: it's the speed of light!

Can this be a coincidence, a numerical accident? Surely not. Maxwell had discovered the fundamental nature of light, light is a traveling electromagnetic wave!

Physicists had struggled for 100's of years to understand light. Newton thought light was a stream of little "particles". But experiments in the early 1800's had shown that light also behaves like a *wave* (with a very small wavelength), e.g. forming diffraction patterns, "bending" around corners, etc… Although light was believed to be a wave, no one knew what was "waving". You don't *need* water molecules, or air, or anything, for light to propagate. And now, in his calculation, Maxwell suddenly showed light must be a traveling EM wave. It's the E and B fields themselves that "wave". The whole idea was deep, profound, and extremely important, it brought together much of known physics into one coherent picture. (We'll be discussing light for the next 3 chapters!)

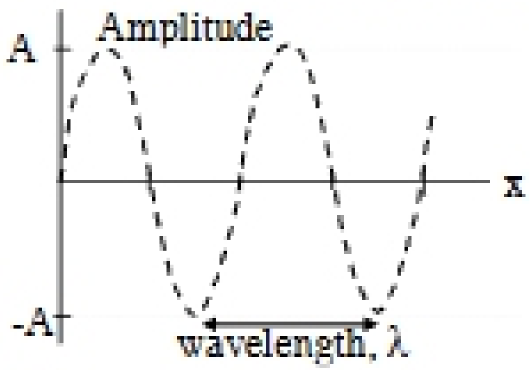
<u>Brief Review of Waves</u> (see Giancoli Ch.11 for more review)

You can watch the <u>amplitude</u> of the waving thing at <u>one</u> point in space (say **x**=0). (E.g. look at |**E**| at the origin)



Period, T= 1/f
f=frequency
[f]=sec^{-1}=Hz

Alternatively, you can take a "snapshot" at some fixed time t. Then you graph amplitude as a function of position.



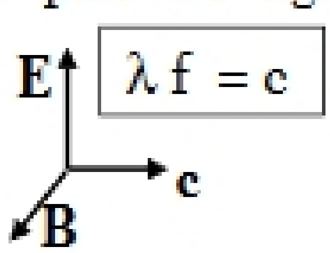
If you take another "snapshot" a moment <u>later</u>, this wave will have <u>moved</u> (to the right, if that's the direction of travel.)
In time T (one period), the wave moves λ (one wavelength) (convince yourself!)

So speed = dist/time = v = $\lambda / T = \lambda f$. (An important formula!)

• For a "slinky wave", those plots show the "transverse displacement" of the slinky.

• For EM waves, the plots show the strength of |**E**| or |**B**| (if you have one, you'll have the other, both E and B "wave" in synch.)

• For EM waves, v = c is a constant of nature.
Giancoli (Fig 22-7) tries to "sketch" a simple, traveling EM wave, heading off in the +**x** direction. Take a look - there are many important things to learn from that sketch, including:



EM waves are "transverse", meaning that **E** and **B** are perpendicular to the direction of travel.

They are also perpendicular to each other.

Waves can be "localized", or not: a "plane wave" (like Giancoli shows) is not "localized" - **E** and **B** are uniform in the y and z directions, but traveling in the **x** direction. (You have to think about that one!)