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!

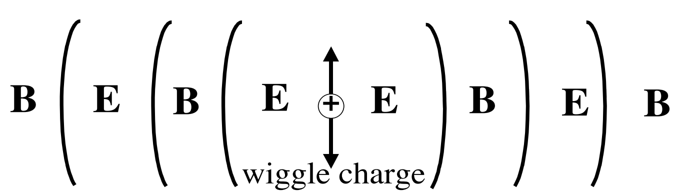
1) **Gauss' Law** : Charges create E, in specific "patterns".
   E fields superpose.
   Coulomb's Law is a "special case".
2) The analogue of 1 for B fields (but, there are no *magnetic monopoles*)
3) **Faraday's Law:** Changing B makes E.
4) **Ampere's Law**: Currents make B

"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.)

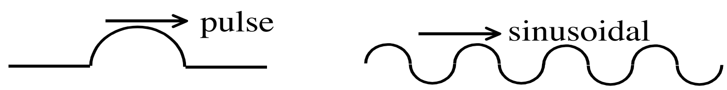
The math of those 4 equations is a little tough (vector calculus is required). There are many consequences, but one in particular is quite remarkable: Imagine shaking a charge "q" up & down.
The E-field is thus "shaking" too. Maxwell's big insight was that a changing E induces (creates) a B-field. But 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* $\varepsilon_0 = 1/(4\pi k) = 8.85 * 10^{-12}$ [C^2/Nm^2]
Experimentally found with pithballs, cat fur, etc. (Ch.16)

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

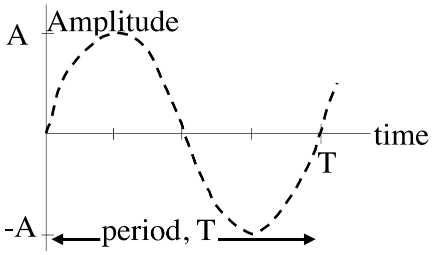
Try to imagine Maxwell's reaction when he came up with this #, because it's very familiar to physicists: it's the speed of light!

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!)

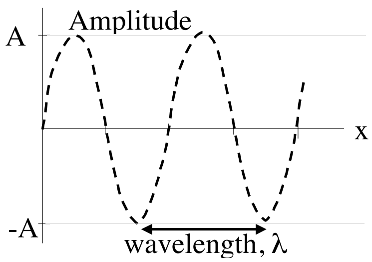
<u>Brief Review of Waves</u> (see Giancoli Ch.11 for more review)

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



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

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



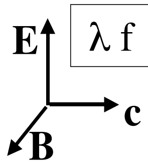
If you take another "snapshot" a moment later, this wave will have moved (to the right, if that's the direction of travel.)
In time T (one period), the wave moves λ (one wavelength) (convince yourself!)

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:



$\lambda f = c$

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!)

Light is a traveling electromagnetic wave.
Visible light has wavelength λ = 400 nm (violet) up to 700 nm. (red)
("ROYGBIV": Red Orange Yellow Green Blue Indigo Violet...)
("nm" = "nano meter" = 10^-9 m) Using $\lambda f = c$, I get
f(yellow) = 3E8 m/s / 600 E-9 m = 5E14 Hz. (A big number!)

You cannot mechanically shake anything 5E14 times/sec! But, some atomic electrons in, say, glowing hot metal *do* shake that rapidly, due to their thermal kinetic energy. Shaking charges emit EM waves (radiation!) with whatever frequency they are themselves shaking at. So, that's *why* hot metal glows visibly - it emits EM radiation.

When this EM wave hits your eye, what happens? There is an E field shaking up and down 5E14 times/sec. Remember, E fields accelerate charges - the electrons in your retina start shaking at that frequency. This causes an electrical signal which goes to your brain, which you *interpret* as an image of yellow-hot metal.

EM waves can have ANY wavelength, there are no "bounds".
400 - 700 nm happens to be visible to our eyes, but other wavelengths are of course possible: it's still EM radiation.
We usually only call it "light" if it's in this range of wavelengths, but in a loose sense, any *other* wavelength EM wave can be thought of as "light", it just won't be visible to our eyeballs...

See Giancoli Fig 22-10 for details of the EM "spectrum".
Here's a brief summary:

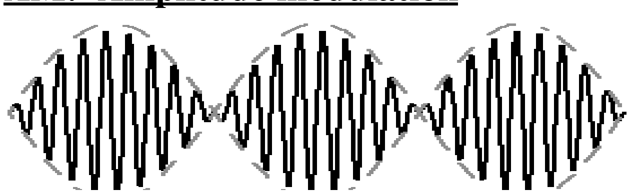
Name	Frequency	Wavelength	Examples
Radio	1E3 - 1E6 Hz (kHz - MHz)	many meters	TV, radio
Microwave	1E8 - 1E12 Hz	cm or so	microwave ovens, radar
Infrared (IR)	1E11 - 1E15 Hz	μm to mm	heat radiation (regular ovens)
visible	1E15 or so Hz	few 100 nm	"light"
Ultraviolet (UV)	1E15 - 1E17 Hz	10's of nm.	tanning lights "black lights"
X-rays	1E17 -1E19 Hz	about 1 nm	medical images
Gamma-rays (γ-rays)	1E19 on up	small!	food irradiation (atom bombs)

TV stations still broadcast in "radio-range", λ is a few meters, f = 100 MHz or so. Your TV antenna (if you still have one, I do!) is metal (length roughly 1/4 of a wavelength). Electrons in the antenna are accelerated back and forth by the passing E field of the TV/radio wave. As the electrons "slosh" back and forth, their motion (it's just moving electrons, an AC current) is detected by a connected circuit and processed to form the sound and images on your set.

Each channel has some particular frequency, f.
E.g., channel 6 (PBS) has a frequency of 86 MHz (??)
with corresponding wavelength $\lambda = c/f = 3.5$ m.
Radio stations also have their own frequency, e.g. "90.1 FM" is broadcasting a radio wave of f=90.1 MHz. ("90.1 Megahertz")
They are *not* broadcasting sound waves directly, it's electromagnetic radiation, with the sound signal encoded. How does this work?

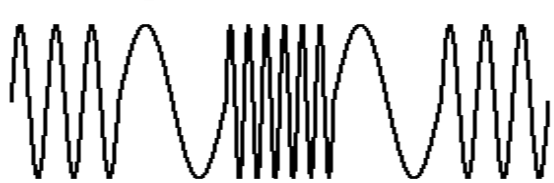
Sound is a *pressure wave* (not an EM wave!) with typical f=1000 Hz or so. Your ear can't detect pressure waves with f >16-20,000 Hz. How can you use 90.1 MHz radio waves to transmit the music? There are several tricks, but you basically "**modulate**" the 90.1 MHz "**EM carrier wave**" with the low frequency signal you want to transmit. Then, in the end, an electric circuit (which can in principle be pretty simple) pushes a speaker cone with that *modulating* frequency, (*not* the carrier frequency!) which pushes air, which makes a pressure wave that you can hear. There are 2 kinds of "modulation" in common use:

AM: Amplitude modulation



The dashed line is a low frequency signal The solid line is the high frequency "carrier". (not to scale!)

FM: Frequency modulation



The amplitude is constant, the frequency is *nearly* constant at the carrier frequency, but with some variation that encodes the signal. (not to scale!)

c is *fast*! It's quite challenging to measure the speed of EM waves. (It's fun to think about how you might go about doing this) *Nothing* known to physics today can travel faster than this.

• When I talk to my friends in Holland, the phone signal goes through metal (or optical) wires, not air, but is still sent as a modulated EM wave, traveling at $\approx$c = 3E8 m/s. The time it takes is roughly t = 10,000 km / 3E5 km/s = 0.03 s, a lag I don't notice.
• When NASA talked to astronauts on the moon, t was about 1 sec (each way) which *was* a noticeable lag.
(We could not hold a normal conversation with astronauts on Mars!)
• From the sun to the earth, it takes light t = 8.3 minutes.
(So, if the sun goes nova, we won't know until 8.3 minutes later :-)
• The nearest star to us, Alpha Centauri, is so far away it takes light around 2 years to get to us. We say α Centauri is 2 light years away. A **light year** is a unit of distance, the distance light travels in a year: 1 ly = c*1 year = 9E15 m.

The farthest visible stars are about 15 billion light years away. Light from those objects was emitted 15 billion years ago, and has traveled at this super-speed right towards us all that time. By now, the object itself is (surely) long gone, but we still see the light it emitted, early in the life of our universe. Very cosmic thought!

<u>Final comments:</u>

• Waves don't carry anything material with them. They do transport *energy*, though. Energy density = 0.5 $(1/2)\varepsilon_0 E^2$ [J/m^3]

• Sunshine carries energy every second. On a typical open patch of sunny land the rate is $\approx$ 1350 W/m^2 (energy/sec/m^2)

• If you stare at the sun, 1350 W/m^2 * (1 mm)^2 = .004 W of power enters your eye. 4 mW sounds small, but this can seriously damage your eye. (Eyes are very sensitive!)

• Light bulbs are 3% efficient, or 97% inefficient. A 100 W bulb consumes 100 J/s, but only 3W is emitted in the *visible* region. (Most of the energy is emitted in the IR, which is sometimes called *heat* radiation, though heat and radiation are really different things.)