

## Electromagnetic Waves

Last semester, we studied Classical Mechanics. The fundamental laws (axioms) of Classical Mechanics are called Newton's Laws, and we were able to write them all down and understand them in their full, complete form.

This semester, we are studying a subject called Classical Electromagnetism. There are four fundamental laws of electromagnetism, called Maxwell's Equations (after the Scottish physicist James Clerk Maxwell). In this course, Faraday's Law is the only one of Maxwell's Equations which we shall actually write down in complete form. The other 3 laws are a bit too mathematically complex to write down in full detail, but we have seen simplified versions of these laws. In words, Maxwell's 4 equations are:

(1) Electric fields are created by charges. (The full form of this equation is called Gauss's Law.

We have seen this equation in a simplified form:  $|\vec{E}|_{\text{due to } Q} = k \frac{|Q|}{r^2}$  .)

(2) Magnetic fields are created by currents. (This equation is called Ampere's Law, and we have

seen this equation in the simplified form  $|\vec{B}|_{\text{due to straight wire}} = \frac{\mu_0 I}{2\pi r}$  .)

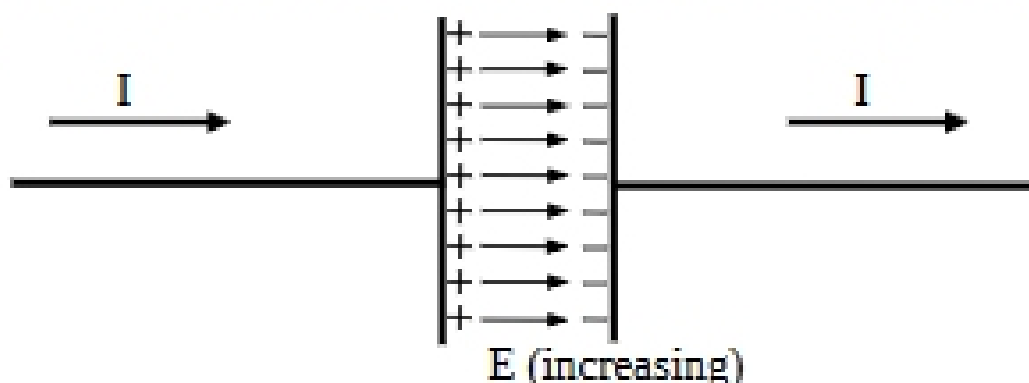
(3) Magnetic field lines always form closed loops. (This equation has no standard name.)

(4) Electric fields are created by *changing* magnetic fields. (Faraday's Law).

Actually, all four of these laws had been discovered experimentally before Maxwell started his research in the 1850's. So why do we call them Maxwell's Equations?

Maxwell made a change to Ampere's Law, equation (2). Maxwell argued, on theoretical grounds, that Ampere's Law must be incomplete; it needs a modification. Maxwell's noticed that there are situations in which a electric current inevitably involves a *changing* electric field. For instance, if a capacitor is being charged up by a steady current, then there must be an increasing electric field between the plates, due to the increasing charge brought to the plates by the steady current.

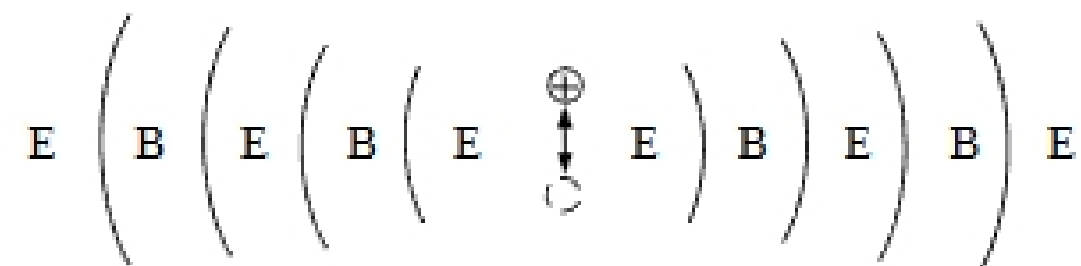
Maxwell's showed that, in order to properly describe such situations,



Ampere's Law must be modified so that it reads "Magnetic fields are created by currents *and* by changing electric fields." This new form of Ampere's Law (now called the Ampere-Maxwell Law) appealed to Maxwell's sense of aesthetics. There was now a pleasing symmetry in the equations:

- changing B-fields create E-fields (Faraday's Law)
- changing E-fields create B-fields (Ampere-Maxwell Law)

Maxwell realized that because of this symmetry, the equations predicted a peculiar kind of self-sustaining interaction between E and B fields. Maxwell thought: Suppose you have a charge  $q$  and you *shake* it, back and forth. The  $q$  creates an E-field, but when you shake the charge, you are changing the E-field in the space around it. This changing E-field creates a B-field. But now you just created a B-field where there was none before, so you have a changing B-field (it changed from zero to non-zero). This changing B-field will create an E-field, and that newly created E-field will create a B-field, which will create an E, which will create a B, which will ... (the process will go on, forever). Maxwell showed that the equations predicted the existence of an *electromagnetic wave* which travels outward from the shaking charge:



Maxwell computed the speed of this strange, new electromagnetic wave and found that the speed

was given by a simple formula:  $\text{speed } v = c = \frac{1}{\sqrt{\epsilon_0 \mu_0}} = 3.0 \times 10^8 \text{ m/s}$ .

This number is the same as the speed of light! Maxwell had shown that light was an electromagnetic wave! Before Maxwell, scientists had no clear idea what light is. This was a great synthesis, a bringing together of previously separate fields of physics: electricity, magnetism, and optics. Before Maxwell, no one knew what light was. It was known that light was some kind of wave (we will see the evidence for this later), but no one knew what kind of wave it was. Maxwell figured it out.

Light is an electromagnetic wave which is created by accelerating electric charge.