General Physics - E&M (PHY 1308) Lecture Notes

Lecture 032: The Nature of Light

SteveSekula, 15 November 2010 (created 14 November 2010)

no tags

Goals of this lecture

- Explain how four equations describing electricity and magnetism came together to explain the nature of light

What is light?

What is light? This is a question that had troubled thinkers and scientists for a long time before the late 1800s. It is capable of carrying information across great distances - witness the light from our sun, which begins its journey 150 million kilometers away and arrives here on earth, delivering energy. It delights our eyes, which are optical systems sensitivity to a rainbow (literally) of colors. But just what is light?

A thing with a definite speed

Light, whatever its nature, was already observed to travel at a great but finite speed. Galileo Galilei, who lived in Italy in the 1500s and was the first *modern scientist*, wondered whether light, like sound, traveled at a finite speed. He devised an experiment to measure this, in fact, but it failed because he did not appreciate just how fast light moves.

You can measure the speed of sound quite easily, by comparison. Get some air horns, a stopwatch, and a few friends. Put one friend on the steps of Dallas Hall with an air horn, another friend 100m away (just south of the "Dedman College" sign on the Boulevard). Have a third friend stand on a bench by the fountain between the Dedman College sign and Dallas Hall. Friend 3 will signal Friend 1 and 2 by waving their arms wildly. Friend 1 will fire their air horn and you'll start the stopwatch when that horn goes off. When Friend 2 hears the first air horn, they will fire their horn. By doing this, you make sound do a round trip from Dallas Hall, to a distance 100m away, and back again. You stop timing when you hear the second horn.

Repeat the experiment, moving Friend 2 a distance 200m away from Dallas Hall. By doing this, you correct for reaction time (the time between hearing the first horn and firing the second horn). Knowing the distance the sound must travel, and the time it takes to make the trip, you can easily calculate the speed of sound.

Profs. Olness and Tunks run a "Physics of Musical Instruments" class with a required lab, and in that lab you do this experiment. You may also have the pleasure of watching your TA swarmed by campus cops while conducting the experiment, because apparently noise on a college campus is a serious law enforcement problem these days.

Sound travels at about 300m/s in air. To make the first round trip, it requires 7/10 of a second. Human reaction time is about 2/10 of a second, so it's a big factor in this first trial. In the second trial, sound has to travel 400m and that takes just over a second (1.3 seconds). Assuming that reaction time is the same in both, and that the speed of sound is the same in both, you can actually obtain a speed of sound that is accurate and has a precision of about 5%. Not bad!

Can we do this with light? Galileo tried. In fact, the above experiment with sound is a modern variation on the one he proposed for light. He put people on distant hills and have them lamps. The first person would open their lamp, sending light to the second person. When the second person sees the light from the first, they open their lamp. The first person stops timing the experiment when the light from the second person arrives. Galileo himself has designed very good clocks, something in high demand in his day. However, human reaction time is 2 tenths of a second, while light actually travels at a speed so great that it crosses the distances in Galileo's experiment much too fast. But at the time, he didn't know that. He learned this by failing to succeed in his experiment.

How fast does light travel, and why can't Galileo's experiment work as designed? Light, we now know, travels at a speed of about $3.0 \times 10^8 \mathrm{m/s}$. The furthest you can see on the earth is about 60 miles, or 100km. Light makes a round trip of 200km in $\sim 0.7 \times 10^{-7}\mathrm{s}$ - far too fast for a human to react with such a simple experiment.

Ole Roemer and Christian Huygens are two scientists credited with determining that light truly travels as a finite speed. A modern interpretation of their work suggests they came within 20% of the correct value. Roemer's work preceded Huygens, and corresponds to a measurement of $2.2 \times 10^8 \mathrm{m/s}$.

The Nature of Sound

Sound is a wave. It occurs when air is compressed by a force, and that compression travels through air. When it strikes the eardrum in the human ear, a series of small bones that can respond to vibration, they cause the bones to shake and that becomes electrical impulses that our brain interprets as "sound". But, regardless of what we hear, sound is just a compression of a medium (air) that travels with a definite speed determined by the mechanical properties of the medium. Sound cannot travel in the absence of air, just as water waves cannot exist without water. All the waves that any scientist had ever encountered up to the late 1800s REQUIRED a medium to travel. The language of waves demanded a medium.

Let's refresh a little on that language. A simple wave is just a variation in amplitude (e.g. air density) that repeats at regular intervals. Such a wave can be described using terms like *period* - the time that passes between similar parts of a wave traveling by you - and *wavelength*, λ - the physical distance between similar parts of a wave.

Using a sine wave as an example, we can easily see the wavelength. The period, T, is just the time it takes for a wave to travel one wavelength - that is, the time for similar parts of the wave to pass you. The *frequency* (f) is just $1/T$, and is the rate at which similar parts of the wave pass you.

The *speed* of a wave is given by distance traveled by the wave in a unit of time. For instance, in one period, T, the wave will travel one *wavelength*. λ. Thus the speed of the wave is given by:

$$v = \lambda/T = \lambda f$$

the product of the wavelength and the frequency.

Sound is fast, but it's not fast enough. For instance, musicians in an orchestra pit have to use two important tools in order to remain synchronized - that is, all be playing at the appropriate times. The first tool is the conductor and the second tool is called "leading the beat". Why do they need tools to stay synchronized? Sound travels slowly enough that if musicians relied on a steady sound to remain synchronized, they would quickly fall out of synchronization enough that the audience would hear it. Your ear is very good at detecting sounds that don't quite arrive at the same time. The orchestra pit is large enough that if you put a timpani player in the center and had them pound out the beat, musicians at the edge of the pit would fall enough behind those in the center that the audience would revolt.

The conductor provides a light-based way of remaining synchronized. The conductor is a visual cue using reflected lighting to tell the players where the beat is. In addition, musicians are AWARE of the limitation of the speed of sound and do something called "leading the beat" where they anticipate the next beat and play a little early. This results in well-synchronized playing across an orchestra pit. Thank goodness for light!

The Fundamental Equations of Electricity and Magnetism

Let us now return to Electricity and Magnetism. We have taken a long but necessary diversion in this story. We have studied many phenomena in this course, but believe it or not you only need a few equations to completely reproduce all observations of electric and magnetic phenomena:

1. Gauss's Law for Electric Fields

$$\int \vec{E} \cdot d\vec{A} = q/\epsilon_0$$

Gauss's Law for Electric Fields summarizes many things:

- electric charge is the source of electric field
- Coulomb's Law is actually a *consequence* of Gauss's Law, though a proof of this is outside the scope of this course. It's enough to know that this is true, and that this means Gauss's Law tells us how charges respond to electric fields
- All the business about electric potential derives from this equation, and combined with conservation of energy we can recover Ohm's Law, Kirchoff's Laws, etc.

2. Gauss's Law for Magnetic Fields

$$\int \vec{B} \cdot d\vec{A} = 0$$

Gauss's Law for Magnetic Fields tells us:

- there are know magnetic charges (at least, none discovered yet)
- magnetic fields equally enter and leave a closed volume of space through the area surrounding that volume

3. Ampere's Law

$$\oint \vec{B} \cdot d\vec{r} = \mu_0 I$$

Ampere's Law tells us:

- that moving electric charge is the source of magnetic field
- the *Biot-Savart* law is a consequence of Ampere's Law, a proof outside the scope of this course. However, this means that Ampere's Law also encapsulates how electric charges *respond* to magnetic fields

4. Faraday's Law

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

Faraday's Law tells:

- that *changing* magnetic flux induces an electromotive force that resists the change

Let's explore this a bit, because Faraday's Law actually tells us something quite profound that is not at first obvious. Recall the definition of electric potential (EMF):

$$\mathcal{E} = \Delta V_{AB} = \int \vec{E} \cdot d\vec{r}$$

Thus a form of Faraday's Law that more purely describes only the behavior of fields is:

$$\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

For a fixed path along which we integrate on the left, this means that *changing magnetic flux induces an electric field*. Casting Faraday's Law this way, we learn one of the most profound things yet:

- Changing magnetic fields induce electric fields

This fact is experimentally verified by my bar magnet/solenoid demonstration - changing magnetic flux induces an electric potential in the conductor that causes current to flow. Without the electric potential - the electric field in the conductor - current cannot flow.

So we have four equations from which all of electricity and magnetism can be expressed:

$$\int \vec{E} \cdot d\vec{A} = q/\epsilon_0$$

$$\int \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{B} \cdot d\vec{r} = \mu_0 I$$

$$\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

They possess remarkable similarities, these equations for electric and magnetic fields. One of them (Faraday's Law) even implies that these two phenomena are intertwined. But it was the genius of a Scottish physicist named James Clerk Maxwell that finally set the stage for a fundamental understanding of light.

James Clerk Maxwell and his Fabulous Equations

Maxwell studied these equations by considering them, and how they would look, in a region of space DEVOID of matter - that is, free of electric charges. This is called "Free Space". In that case, these four equations take a simpler form:

$$\int \vec{E} \cdot d\vec{A} = 0$$

$$\int \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{B} \cdot d\vec{r} = 0$$

$$\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

No currents, because there are no charges to move; and no charges of any kind. We see a wondrous thing happens - Gauss's Laws for Electricity and Magnetism are now *perfectly symmetric* - that is, in the absence of matter they describe two fields that behave the same way. But what about Ampere's and Faraday's Laws? They are close, but not exactly symmetric. This is where Maxwell's genius is revealed.

Maxwell took a leap. He asked what would happen if, in fact, these equations WERE perfectly symmetric. So he added a term,

$$\oint \vec{B} \cdot d\vec{r} = C\frac{d\Phi_E}{dt}$$

$$\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

to Ampere's Law in free space.

What is this term? It implies that a changing ELECTRIC flux could induce a magnetic field. In fact, this is not just a math trick - this is true scientific hypothesis. Maxwell looks at Ampere's and Faraday's law and makes a scientific hypothesis: that these two equations should be perfectly symmetric, and that requires a changing electric field to induce a magnetic field. This then leads to a prediction: that this phenomenon should occur. At the time, nobody had measured such a thing, but experiments followed and verified the hypothesis, turning it into a theory: the theory of electromagnetism.

These four equations are now known as $Maxwell's\ Equations$, honoring his deep insight into the subject. In "free space" these equations take the form:

$$\int \vec{E} \cdot d\vec{A} = 0$$

$$\int \vec{B} \cdot d\vec{A} = 0$$

$$\oint \vec{B} \cdot d\vec{r} = \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

$$\int \vec{E} \cdot d\vec{r} = -\frac{d\Phi_B}{dt}$$

But what do they describe? What are these equations FOR?

Electromagnetic Waves

The above equations describe what is known as an *electromagnetic wave* - a time-varying set of electric and magnetic fields, described by sine functions. They behave just like sound waves or water waves, and should be describable using the same language - period, frequency, wavelength, and speed.

It was when the question of *speed* was tackled that an amazing thing happened. Upon calculating the speed at which electromagnetic waves travel in free space, it was seen that this speed is given as:

$$\frac{1}{\sqrt{\mu_0 \epsilon_0}} = c = 3.00 \times 10^8 \mathrm{m/s}$$

The *speed of light*. So it's no coincidence, in fact, that this product of electric and magnetic constants yields the speed of light. It's on purpose: light is an electromagnetic wave.

This revelation from Maxwell's Equations made it possible to invent wireless transmission of information - radio. The principle is simple. You build one device that uses a time-varying electric field to generate electromagnetic waves. These waves then travel at the speed of light over vast distances. A second devices is located elsewhere and can convert the electromagnetic wave - time varying electric and magnetic fields - into moving electric charge. This can then be used to reconstruct the original signal. Radio, TV, and now mobile communications all use this principle. Without Maxwell's Equations, we might never have been able to achieve this understanding of light as varying electric and magnetic fields.

The Nature of Light

Light, in all its forms, is a pair of electric and magnetic fields traveling through space. Light originates from moving charges (according to Maxwell's Equations).

But if light is a wave, in what medium does it propagate? After all, all other waves - water, sound - need a MEDIUM to travel. Yet, Maxwell's Equations describe waves moving in an ABSENSE of matter.

This seeming paradox set physicists on a quest to discover the medium in which light travels, which was dubbed "The Aether." A series of experiments over decades culminated in a very precise set of experiments known as the *Michaelson-Morley* experiments. They were confident that their work would unveil the existence of the aether. It was so precise that it more than matched all the mathematical expectations for detecting the presence of this mysterious substance.

They saw nothing.

It was the most famous *null result* in history. They are famous for never seeing anything. Why? Because a young man, laboring in a Swiss Patent Office in Bern, Switzerland (so that he could support his family until he got a university job), accepted the results of the *Michelson-Morley* experiment. Not only that, he accepted that Maxwell's Equations were utterly correct an inerrant - that they described light as something that needed to medium to travel and that all observers, regardless of their speed, measure the speed of light to be the same - a universal constant. His name was Albert Einstein, and his acceptance of these things led to three papers in 1905 that changed physics, and the world, forever.

The Legacy of Electromagnetism

From a complete understanding of electromagnetism as a single, fundamental force came a revolution in physics. In one year, Einstein combined seemingly incongruous observations of the natural world and mathematics into the first proof for the existence of atoms, the first persuasive argument that light was not just a wave but also acted like a particle under certain conditions, and the bold statement that our understanding of light was perfect but our understanding of space and time was wrong (the special theory of relativity).

In 1905, we saw the seeds planted for the modern world: quantum mechanics, the laws of very small scales; and relativity, the laws of things moving very fast and on very large scales.

And all of this from recognizing that light is an electric and magnetic phenomenon.