Physics 419
Lecture 8: Wave, Electricity and Magnetism: The Aether Front and Center
Feb. 18, 2021

1 Themes

The problems in Newton's world were not settled by further investigations into the properties of gravity but rather from the field of electricity and magnetism. Today we will show how this came about. Recall the aether as a physical causative thing was created by Descartes to account for forces bodies exert on one another when there is no direct contact between the bodies. The aether acted like a bunch of vortices that swirled bodies around creating action at a distance. Precisely how this idea should be tested was a big mystery and the precursor to testing it is the object of today's lecture.

- Waves
- Fields
- Speed of Light
- Search for the Aether

2 Waves

Wave phenomena are important for the development of special relativity and in the understanding of quantum mechanics, so here is a brief classical description of waves.

Consider waves in a string, on water, or in air (sound). They all share several features. These waves are not independent constituents of the world, just a mode of behavior of matter obeying force laws.

1.) There is a medium which is normally at rest, or at least is undisturbed. (Air might be moving uniformly.)

2.) The wave is a disturbance in the medium. Pluck the string, or create a high pressure region in the air.

3.) A wave moves through the medium with a velocity with respect to the medium. This velocity might depend on the shape or height of the wave.

4.) An ordinary wave is spread out over a range of positions and also is travelling with a range of velocities in different directions.

Intensity: The amount of energy carried by a wave is proportional to the square of the amplitude (height) of the wave. Even where the wave is negative it has positive energy.

Interference: The result of adding two waves depends on whether they are ”in phase” or ”out of phase”:

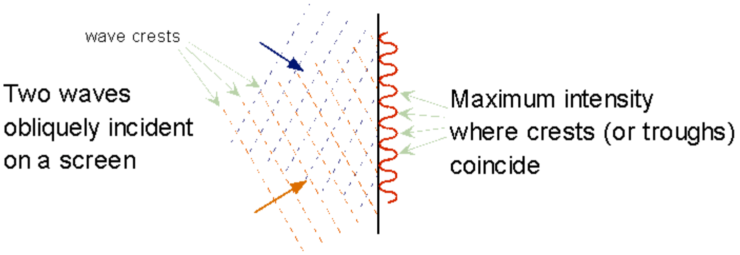

Figure 1: Interference of waves

At a given point, the effect of two waves together can be less than either one separately.

Sometimes we make an important practical distinction between wave packets (”pulses”) and periodic waves: (e.g., on a string)

Waves ...

The wave moves at some speed with respect to the medium. This means that one can learn about the motion of the medium by observing only the wave.

Doppler effect. If the source of a wave is moving towards the observer, or the observer toward the source, the crests become squeezed together. More of them pass the observer per second, and the frequency is higher. This is the cause of the familiar ”train whistle” effect.

The classical formula for the Doppler effect depends on both the velocity of the observer wrt the medium and the velocity of the source wrt the medium, NOT just on the relative velocity of the observer and source. Consequently, a moving observer and a moving source will be not be equivalent, except for light of course.

E.g. if the observer is moving away from the source at the wave-speed, the observer, will never detect the wave. She will just be able to out run it. This is not the case when the source moves away from the observer, however. Regardless of how fast the source moves away from the observer, the waves will eventually get to the observer. Its just that the frequency will be greatly reduced.

If the observer moves away at 1/2 the wave-speed, and so does the source, the observed frequency will be 1/3 of the source frequency. Note, the relative source-observer speed is the same as above in the example

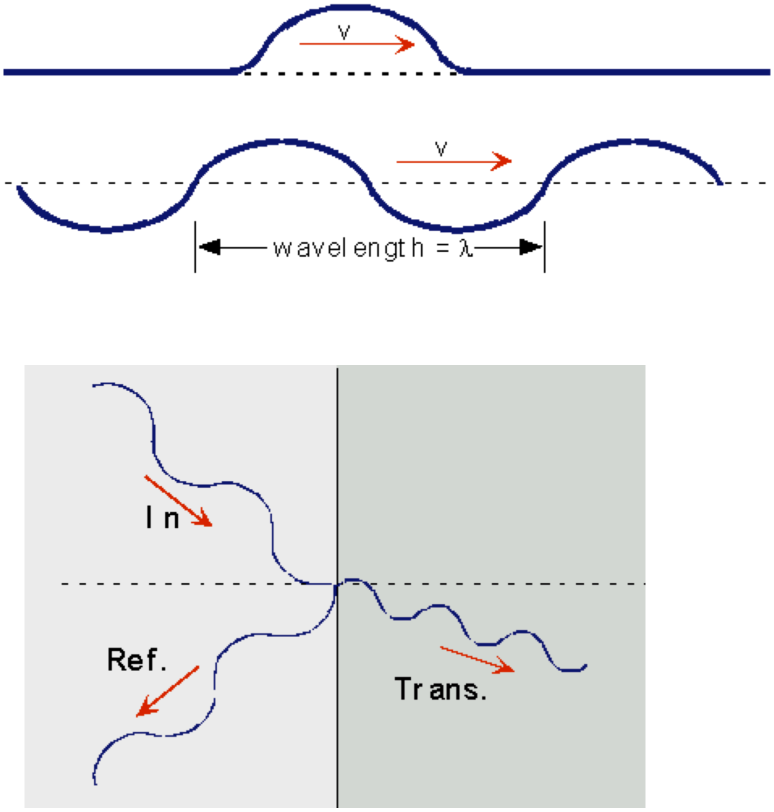

Figure 2: Standing waves and reflection and transmission of waves.

above where the observer never hears the sound if she moves away from the source at the speed of sound. This example illustrates the asymmetry between a moving observer and a moving source. Don't worry if you cannot reproduce these numbers. The key thing is that you understand that with traditional waves, there will be a difference between a moving source and a moving observer.

3 Electricity and Magnetism

The fundamental force involved in most experiences is electro-magnetism. We won't follow the historical development (Franklin, Coulomb, Ampere, Faraday, Maxwell's) but will just give the result, which bears a strong resemblance in general form to gravity.

Field: We should also mention the notion of a field. Every electrical current is surrounded by a magnetic field. Magnetic fields are generated any time electrical charges move. This field has an ability to exert a force. It is for this reason that the magnetic force law has in it the velocity of the moving charged particles. Likewise, every electrically charged object is surrounded by an electric field. This electric field will generate a force on any charge in its vicinity.

There is a property of each object called its charge, q.

The electric force between two charged objects is given by

$$\mathbf{F} = \frac{q_1 q_2}{r^2} \quad \textbf{Electricity}, \tag{1}$$

which should remind you of the law of gravity:

$$\mathbf{F} = \frac{GM_1 M_2}{r^2} \quad \textbf{Gravity}. \tag{2}$$

There's another force, magnetism, between electrically charged objects with some velocity:

$$\mathbf{F} = \frac{q_1 q_2 \mathbf{v_2} \times (\mathbf{v_1} \times \mathbf{r})}{r^2} \quad \textbf{Magnetism} \tag{3}$$

Note: The magnetic force depends on the velocity per se, not on relative velocities. This magnetic force law gives a different result if you add some velocity to both v_1 and v_2. Also, you have two charges and two forces between them. In the case of gravity, you have tow masses and one force between them. Why do gravity and E&M differ so manifestly?

Galilean relativity is broken by the magnetic force law! This should tell you something. It turns out that time-reversal symmetry is also broken by a magnetic field. More on this later.

Did Galilean relativity apply only to some mechanical laws, but not really to the laws of physics as a whole? Is there some other relativity that works?

A Closer look at Fields

One of the most worrisome features of Newton's theory of gravity was that it required objects to affect each other across empty space. Newton thought that there must be some mediator, but he did not know what it was.

With the study of electricity and magnetism it became useful to distinguish the source of an effect from the object of its "effection". It was noticed that for all three forces (gravity, electricity, and magnetism), the effect of an object on any other object can be written as the product of two terms, one depending only on the first (called the source) and the other only on the second.

$$\mathbf{F} = \frac{GM_1 M_2}{r^2} \equiv \mathbf{g} m \quad \mathbf{a} = \mathbf{g} \tag{4}$$

g is the gravitational field.

Consider electricity

$$\mathbf{F} = \frac{q_1 q_2}{r^2} \equiv \mathbf{E} q_2 \quad \mathbf{E} = \mathbf{ElectricField}. \tag{5}$$

Magnetism can be couched equivalently in terms of a magnetic field:

$$\mathbf{F} = \frac{q_1 q_2 \mathbf{v_2} \times (\mathbf{v_1} \times \mathbf{r})}{r^2} \equiv q_2 \mathbf{v_2} \times \mathbf{B} \quad \mathbf{B} = \mathbf{MagneticField}. \tag{6}$$

The field is a useful mathematical device, but the question naturally arises, are these fields “real”? In order to be real, they ought to have some independent manifestation (besides just a simple way to calculate forces between objects).

4 Electromagnetism and the Aether

Electric and magnetic fields were discovered in the 19th century to have two properties which gave credence to their reality.

1.) Faraday discovered that if the magnetic field B varies with time, this gives rise to an electric field E. The reverse is true as well. So, there is some behavior of E and B which is not merely a simple force calculation.

2.) James Maxwell developed a theory in 1864 which implied that E and B can exist in the absence of any electrical charges (i.e., no sources). He unified the description of electricity and magnetism and claimed that light is a wave composed of oscillating E and B fields. He predicted the existence of ”electromagnetic waves” which were observed by Hertz.

Three previously distinct phenomena have been subsumed by a single theory. (term paper topic)

Two problems arose immediately.

1.) When an EM wave propagates through the vacuum, what is the medium? What is oscillating?

2.) The equations which describe electrodynamics violate Galilean invariance. This violation should show up in the wave motion. Is the speed of light uniform only with respect to the medium? (Dubbed the luminiferous ether.)

Does the Earth Move?

The Problem:

Maxwell's equations describing electrodynamics violate Galilean invariance. They contain an absolute (not relative) speed.

Consider the wave equation, which describes the motion of radio and light waves (E is the electric field):

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} \tag{7}$$

The feature of immediate concern is the c in the denominator. This is the speed at which the waves move, and its presence in the equation is not good for Galilean relativity, even though the equation is pretty. c does not change relative to any frame. It is fixed. How can this be the case if we accept Galilean invariance? This was the initial motivation for Einstein's work on Special Relativity.

Galilean relativity says that if one person observes an object to have a certain velocity another person (who is moving) will observe a different velocity. Maxwell's equations don't seem to accommodate this behavior for light, because the equation doesn't say to use a different c for different observers.

How does one try to solve the problem?

If one is a late 19th century physicist, the natural guess is that c is the speed relative to the aether, NOT to any old observer. You should think about this seriously.

Why look for the aether?

By analogy with the behavior of other waves (e.g., sound and water waves) it was natural to expect light waves ("light" means any electromagnetic wave) to be carried by a medium. The aether might transmit other long distance effects, such as gravity, as well. Without the ether, the alternative solutions to the problem were not very palatable. ("Are you saying relativity is wrong?" No.) It offered the possibility of a resolution of the Newton-Leibniz (i.e., the substantivalist-relationist) debate. If the ether exists, then it becomes a candidate for Newton's absolute space. (Sklar, Space, Time,& Spacetime, p. 196) If the ether takes over the role of absolute space, there is now just one reference frame in which you can use the simple laws of physics (Maxwell's equations.) Galilean relativity would be out the window.

A careful experiment could either verify or falsify Maxwell's equations in the observer's frame, and thus say in a meaningful way if that frame is moving.

How to look for the aether:

If you are moving through a medium, the observed speed of the wave will vary with direction. The apparent direction of a source will vary with the observers velocity (aberration, see Rohrlich, p. 53). These effects are not large. The largest speed you have easy access to is the speed of the Earth in its orbit, about 30 km/s, which is about 10^{-4} c. (rotating around some unknown average velocity)