Modern Physics (PHY 3305) Lecture Notes

The Beginning of the Modern Era

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tags: lecture

CHAPTER 1

This lecture will cover:

- the goals of the class (syllabus, class structure, homework, tests, presentation)
- a review of the triumph of Newtonian physics
- the failures of the Newtonian view
- first thoughts about relativity, including how to think about light and the speed of light, how to understand frames of reference

The Goals of the Class

Review the syllabus briefly, discussing expectations for the course: homework, office hours, exams, and the presentation.

The Triumphs of Newtonian Physics

Here we will discuss quickly the statements and achievements of Newtonian physics. Beginning with $F = ma$, which united the actions of the heavens and those of the earth, we will review the achievement of the mechanical view of nature. We will also review electricity and magnetism, including the revelation that time-varying magnetic fields produce electric fields and time varying electric fields produce magnetic fields. This representing the uniting of electricity and magnetism into a single electro-magnetic idea.

Newtonian physics refers to the laws of nature developed by Newton and extending forward 200 years through the 1800s. This is a large body of work that stemmed from Newton's original laws of motions, themselves based on observations of the natural world. The recognition that force and acceleration are directly related to one another through inertial mass ($F = ma$) was a fundamental statement that the behavior of objects on earth and the behavior of the stars, the sun, and all other bodies all stem from the same principals. Newton's ideas united the heavens and the earth, and represented the first logical and fundamental unification between seemingly disparate phenomena.

There were many successes that stemmed from this work:

- Kepler and others derived predictions of the motions of heavenly bodies based on Newton's laws of motion. This predictions was stunningly accurate, with only a few exceptions (the perihelion of Mercury).
- Energy was recognized as a fundamental quantity that was neither created nor destroyed, but transferred from one body to the other. Any losses incurred along the way were recognized as energy going into processes (e.g. heat) other than the intended one (e.g. motion).
- Mass was recognized as a body's tendency to resist motion (inertia), and was something that could be quantified by the laws of motion.
- Light was identified as a wave phenomenon, owing to the behavior of light when it (a) scattered around small objects (interference) (b) . . . .
- Electricity and Magnetism were revealed as two faces of the same underlying phenomenon - Electromagnetism. All electric and magnetic phenomena can be described as waves; in fact, here light was identified as alternating electric and magnetic fields propagating at the speed of light ($2.995 \times 10^8 \mathrm{m/s}$). It was assumed that, as for all other wave phenomena, light propagated in a medium (the ether) and was affected by motion of that substance, or motion relative to that substance.

A coherent, mechanical picture of the universe began to emerge - the universe as a perfect machine. Thus is was assumed that measurements were limited only by the instrumentation, and that with perfect measurements of initial conditions the exact outcome of any situation can be determined before it occurs. The behavior of the physical world was perfectly deterministic, governed by the mechanical laws of nature (nature as a ticking clock). All the universe plays out on the stage of space and time, which are absolute concepts unchanged by the state of the observer.

The Failures of Newtonian Physics

Here we will discuss a few examples of where the triumphs necessarily led to failures. The mechanical view of the universe suggested that space and time are the same for all observers, regardless of their state of motion (consider the case of a person dropping a ball while standing still, vs. doing so while walking and being observed by a person at rest). Energy *(motion) is different from mass, and both come in continuous units. All things could be predicted, and this extended to the energy of a blackbody whose spectrum was INCORRECTLY predicted by these notions. The laws of electromagnetism predicted that EM disturbances all travel at the same speed, the speed of light, independent of any propagating medium. Worse, the classical need to invoke such a medium led to the observation that the speed of light is the same for all observers, regardless of their state of motion (Michelson-Morley).*

- Light appears to be unaffected by the motion of the observer: the experiments of Michelson and Morley. This made no sense, yet experiments repeatedly failed to prove the existence of an ether and our motion through it. Worse, the laws of Electromagnetism ("Maxwell's Equations") appeared "special", in that their form changed depending on the state of motion of the observer. Using a Galilean transformation, where $x' = x - vt$ and $t' = t$, all the mechanical laws of nature remain unchanged but Maxwell's Equations change radically and made untenable predictions.

- The theory of heat failed to predict the energy emitted by a blackbody. If heat is described as thermal motion of atoms in a body, and we consider heat trapped in a cavity (the perfect blackbody), the emitted spectrum of energy becomes infinite as the energy of the emitted radiation increases. This ultraviolet catastrophe would result in the destruction of the universe if even one blackbody were in existence, yet the measured spectrum of energy emitted from real blackbodies showed that it increased and then cutoff.

Break

Building Comfort with Reference Frames and the Speed of Light

Review a few examples of reference frames and do some exercises with the speed of light. These will be used to get the minds flowing and focused on meaning and interpretation. Some useful examples would be:

- *Everyday speeds: walking, cars, baseballs, bullets, planes.*

- *Compare the speed of sound and the speed of light and apply those differences to real problems*
    - *Lightning and thunder - estimate the distance to the storm*
    - *Synchronizing the symphony - why you need a conductor*
- *Then think about time and space*
    - *discuss the speed of light over astronomical distances*
    - *what does it mean to "see" a distant star? Use the big dipper as an example, since that is ~70 ly away and thus has relevance to the scale of human existence.*

Let's build some comfort with terms and ideas we will encounter routinely in this course.

- **Relativity**
    - What is "relativity"?
        - In the Galilean sense, while you and I may DISAGREE on the sequence of events during an experiment conducted when I am at rest and you are in motion (e.g. the dropping of a ball), we do AGREE on the results and thus that the laws that govern the motion are the same for both of us and thus we can TRANSFORM results from one frame into those in another.
        - The Galilean Transformation accomplishes this (examples: cars on a freeway, catching a pass in football being easier when you are running away from the passer, etc.)
    - What is a "reference frame"?
        - a system of coordinates defined for an observer. It is "standard" to put the observer at the origin of the system and define all distances relative to that point.
            - "I am at the origin," says one observer, at rest and watching a second observer in motion. "No," says the second, "I am at the origin." They are both right, in that each has their own origin. Again, relativity of space.
    - What is "simultaneity"?
        - Turn English into Math. Discuss how Math is a way to express ideas describable in language, but in and of itself is also capable of describing things for which there are no words. English into Math is easy, but Math into English is not always easy.
        - Will two observers always agree that two events are simultaneous? Think about this in the Newtonian sense. Think about this light people in the 1800s would think about this.

- **Speed of Light**
  - How fast is the speed of light? How does it compare to speeds in our everyday life?
    - Consider walking, running, sound waves. Discuss "orders of magnitude"
    - Discuss synchronizing a symphony. Can you do it with sound alone?
    - Discuss what it means to "see" distant stars and galaxies. Use the Big Dipper as the finale example for this class period.

Useful numbers:

- speed of walking: about 1 m/s
- speed of running: about 2-3 m/s
- speed of driving: about 25 m/s at highway speeds (~10x more)
- speed of flying/sound: about 100-200 m/s (343 mph for sound), or 10x more
- speed of navigational satellites: about 1000 m/s, or 10x more
- speed of light: 3×10^8m/s, or about 5 orders of magnitude faster than satellites in orbit

Synchronizing a Symphony

The conductor of an orchestra is not for show. A conductor is not just a part of the social construct of the orchestra. A conductor is not just a means by which one person can be made more important than another. The reality is that the conductor of an orchestra is required, by the speed of sound and the speed of light, to exist.

What do I mean by this? Let's consider the human head. The distance between our two ears is about 22cm (about 8.5 inches). This distance means that sounds that are not originating from directly in front of us reach our two ears at different times. The human auditory system is capable of discerning sounds that are no more than 0.000660 seconds apart from one another – that's 0.660 milliseconds (ms) [1]. The result of this ability to process signals which arrive more than 0.660 ms apart is that we can localize sound in space. This process, called "Duplex theory," means that if sounds are closer than 0.660 ms then they cannot be localized; we lose the ability to distinguish the sounds, and they seem to arrive at the same time.

So, what does this have to do with the conductor of an orchestra? Let's *imagine a situation where the orchestra, full of spite for the primadonna conductor, decides to go completely democratic and tosses the tyrant out onto the street. “We can synchronize ourselves!” they proclaim, and they turn to the oboe player.*

“Oboe player, sit in the middle of the orchestra pit and blow a series of tones in the tempo of the song! That way, we can listen for the tempo and mark the passage of time, so that we, too, can stay on time.”

This seems like a great idea. Sadly, the universe has conspired against this democratic process. Sound travels at about 300 m/s. As a result, it takes 0.033s, or 33ms, for sound to travel even the 10 meters from the center of the pit to the outermost players (assuming a 20m-diameter pit). The result is that a player on the outskirts of the pit hears the oboe’s beat 33ms after a player next to the oboe hears it. Players on the outside of the pit are 33ms LATE in playing their instrument.

What does this mean? It means that the players on the outskirts of the pit become unsynchronised from their center-pit colleagues. Is this a bad thing? YES. Since the human ear is capable of hearing the difference between sounds that are at least 0.66ms apart, and the sounds from the inside and outside of the pit are 50 times further apart than that in time, the whole orchestra sounds like they’re playing out-of-time. The resulting cacophony will surely cause ticket sales to plummet, and our democratic orchestra will go flat broke.

The conductor, on the other hand, standing in front of the orchestra, uses light, not sound, to synchronize the orchestra. Since light travels at about 300,000,000 m/s, it takes just 0.000067 ms for their hand gestures to be seen by players at the back of the pit, compared to those closest to the conductor. This means that players are just 0.000067 ms out-of-time with one another; this is vastly below the human ability to hear the difference between two sounds, saving the orchestra and insuring a flawless performance.

Thunder and Lightning

The light and sound travel the same distance, d. The time the light requires to go from the storm to us is shorter than the time for the sound. The time for the light is $t_l = d/c$, where c is the speed of light (300,000,000 m/s). The time for sound is $t_s = d/v_s$, where v_s is the speed of sound (300 m/s). We are interested in the number of seconds between the sound and the light, so let’s compute the time difference using these formula:

$$t_s - t_l = d/v_s - d/c = d(1/v_s - 1/c)$$

We can rewrite the quantity $(1/v_s - 1/c) = (1/300 - 1/300,000,000) = 1/300(1 - 0.000001)$*, which is (to a very good approximation) 1/300.*

We arrive at our final relationship:

$$t_s - t_1 = d/300$$

*where time is in seconds and distance is in meters. So, if we are sitting on our patio and we see the flash of lightning, and then 6 seconds later we hear the thunder, the storm is (6s * 300 m/s) = 1,800 m, or about 1.1 miles.*