Toward Completing Classical Physics

Intro to waves
Intro to electro-magnetism

- HW3 due Thursday, Feb 12th.
- Quiz next Thursday, Feb 19th on relativity:
    - short answers. 20 mins. Closed book.
    - Materials from Rohrlich pgs.34-88, Cushing Chpts. 13,16-17, Sklar pgs. 25-40 & class notes.

Energy: Thermodynamics

- Joule: there is a huge amount of stored thermal energy. Raising the temperature of water by 1° C takes as much energy as getting it going 90 m/s (~350 mph).
- Extending energy conservation to conversion between thermal and mechanical forms is the 1st law of thermodynamics.
- Conservation of energy is not the whole story. While it is possible to convert all mechanical energy into heat (*e.g.*, by friction), *the reverse is not possible.* Overall, mechanical energy is inevitably lost to heat. .
  - Carnot first realized this ~1820. One consequence is that there cannot be a perpetual motion machine.
  - Carnot's analysis of irreversibility was done using the caloric theory. We shall preserve his connection between water running downhill, and heat flowing to colder regions, but put both in a broader context, when we return to this topic.

An implication of thermodynamics: Heat death of the universe (Kelvin, 1852)

- The second law implies that the universe will eventually "run down." The stars will burn out, etc. Doesn't fit with the simple notion of an eternal universe.
- We'll discuss the origin and fate of the universe at the end of the course.

Newtonian cosmology

- The universe must be infinite for several reasons:
  - A finite one has a center and edge (*i.e.*, absolute position).
  - Hard to reconcile Euclidean geometry with a finite universe.

However, an infinite universe has at least two problems:

Olber's paradox:

In an infinite, homogeneous universe, whichever direction one looks there will eventually be a star, so the night sky should be bright.
you can imagine ways around this problem

- (*e.g.*, dust),
- Actually, dust doesn't work in an infinitely old universe. The dust would just heat up and glow like a star.

Can the universe be infinitely old? What about the finite stellar lifetime, from conservation of energy?

- Mathematical problem: There are no steady solutions to the equations that describe a gas-like collection of , a bunch of things whizzing around, with gravitational interactions.

  This issue will come up again in general relativity.

Waves

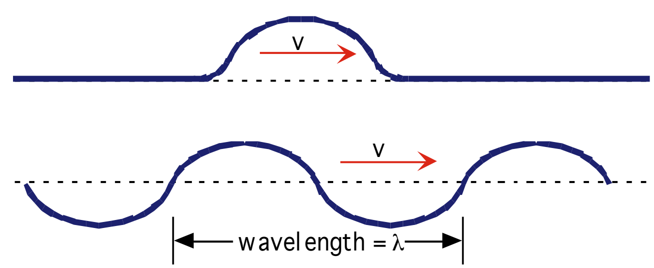
Wave phenomena are important for the development of special relativity and for understanding quantum mechanics, so here is a brief classical description of waves.

Waves in a string, on water, or in air (sound) all share several features.

- These waves are not independent constituents of the world, just a mode of behavior of matter obeying force laws.
- There is a medium which is normally at rest, or at least is undisturbed.
  - E.g. air might be moving uniformly.
- The wave is a disturbance in the medium.
  - Pluck the string, or create a high pressure region in the air.
- 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.
- An ordinary wave is spread out over a <u>range of positions</u> and also is travelling with a <u>range of velocities</u> (even when the speed is fixed, there's a range of directions.)

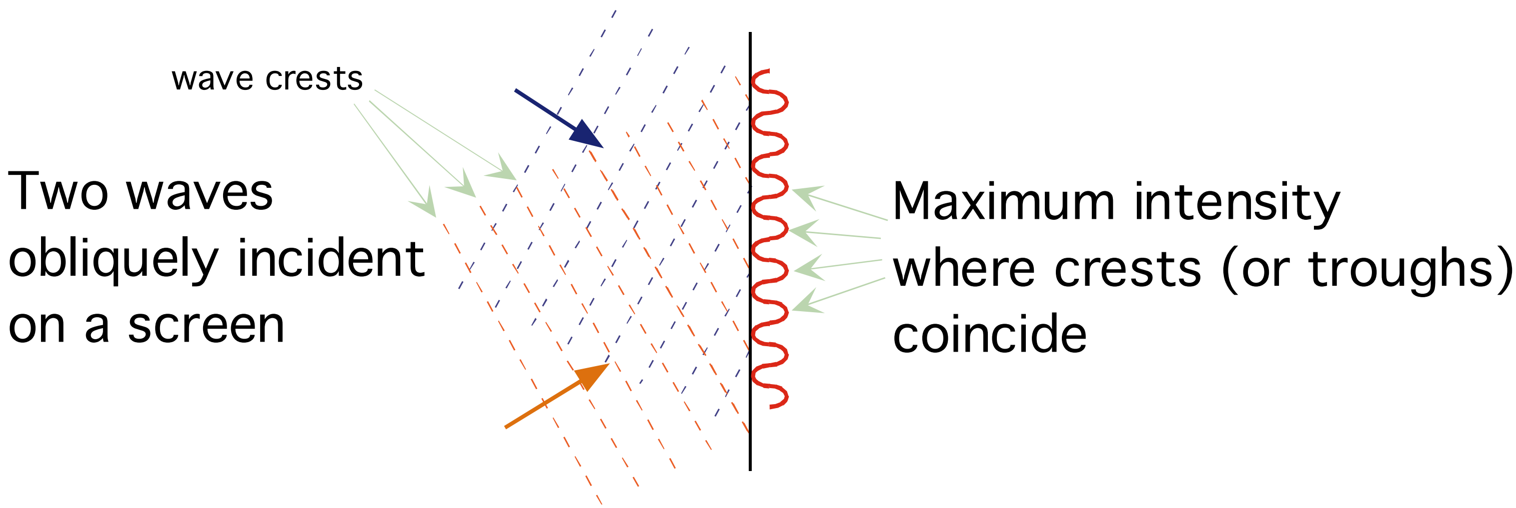
Waves can come in various packets, with a range from

pretty well-defined positions
to
pretty well-defined wavelengths.



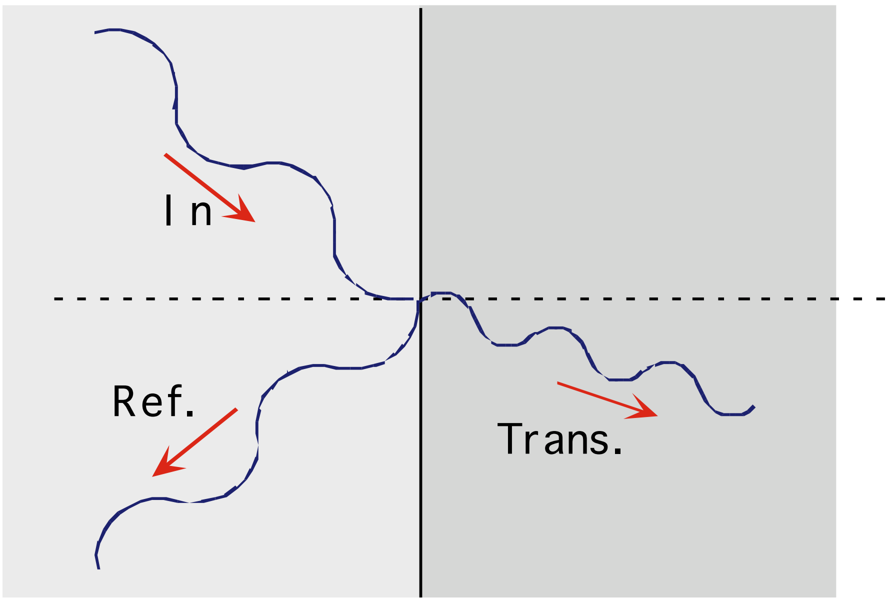
Wave properties

- **Intensity**: The amount of energy carried by a wave is proportional to the <u>square</u> of the amplitude (height) of the wave.
  Both negative or positive amplitude have positive energy.
- **Interference**: The intensity of adding two waves depends on whether they are "in phase" or "out of phase" or in-between:
- $(a+b)^2 = a^2+b^2+2ab \neq a^2+b^2$, so $I_{a+b} \neq I_a+I_b$

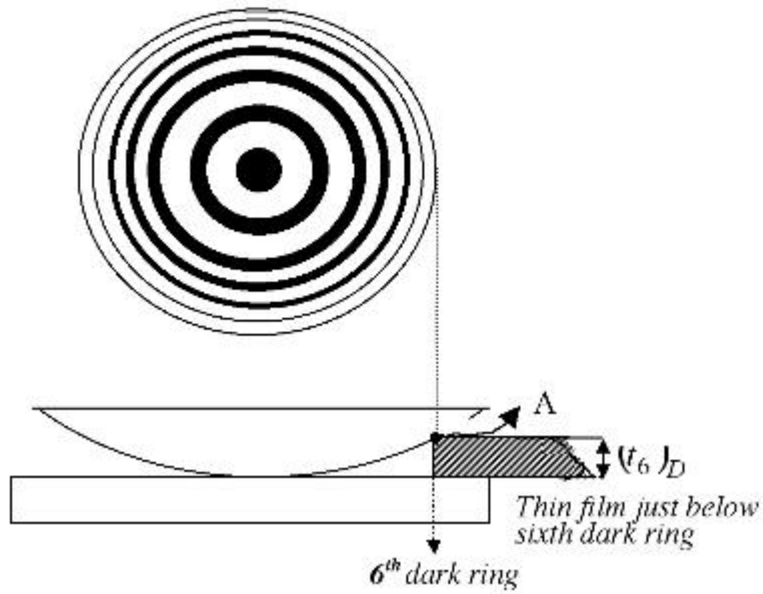


- At a given point, the intensity of two waves together can be less than either one separately.
- Energy conservation still works because at other points the intensity is greater than the sum of the separate intensities.

Refraction and reflection

- Waves are refracted and partially reflected at a boundary:
- 

Newton's fits of easy and hard refraction?



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Wave properties

- The wave moves at some speed with respect to the medium. So 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.
  - E.g. if the observer is moving away from the source at the wave-speed, the observed frequency will be ZERO regardless of the details of the source motion.
  - E.g. 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. The *relative* source-observer speed is the *same as above*, but *1/3 is not the same as zero*.

Electro-Magnetism

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

Electricity:

- There is a property of each object called its charge, q.
- The electric force between two charged objects is given by: $F = \frac{q_1 q_2}{r^2}$

which should remind you of the law for gravity: $F = \frac{GMm}{r^2}$

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

Magnetism:

$$\vec{F} = \frac{q_1 q_2 \vec{v}_2 \times \left(\vec{v}_1 \times \hat{r}\right)}{r^2}$$

What is different about this force?

Galileo's Relativity Gone?

- *The magnetic force depends on the velocity per se, not on relative velocities.*

This force law gives a different result if you add some velocity to both v_1 and v_2.

- <u>Galilean relativity was broken by the magnetic force law!</u>

- 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?

- Isn't that possibility just what Newton's philosophical ideas about absolute space had suggested?

- If we assume some ether which is the medium in which E-M waves propagate, might it not also provide the only reference frame in which Maxwell's equations are true? (i.e., only one at rest wrt the ether)

  plus maybe provide the medium Newton wanted for gravity?

- Would we then have all spatial properties be purely relational, but against a background of simple ether properties which mimic Euclidean space?

Action at a Distance and 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. N 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 object (called the source) and the other only on the second object.

- Gravity: $$\vec{F} = \frac{GMm\hat{r}}{r^2} \equiv \vec{g}m \qquad \vec{a} = \vec{g}$$
- Electricity: $$\vec{F} = \frac{q_1 q_2 \hat{r}}{r^2} \equiv \vec{E}q_2 \qquad \vec{a} = \vec{E}q_2 / m$$
- Magnetism: $$\vec{F} = \frac{q_1 q_2 \vec{v}_2 \times \left(\vec{v}_1 \times \hat{r}\right)}{r^2} \equiv q_2 \vec{v}_2 \times \vec{B}$$

- ***g***, ***E***, and ***B*** are called the gravitational, electrical, and magnetic fields, respectively.
- The field is a useful mathematical device, but are these fields "real"? How to tell?

In order to be real, they ought to have some *independent manifestation,* besides just giving a simple way to calculate forces between objects.

Electromagnetism and the Ether

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

- Faraday discovered that if the magnetic field **B** varies with time, this gives rise to an electric field **E**.
  - So, there is some behavior of **E** and **B** which is not just a re-description of forces between particles.
- James Maxwell discovered (1864) that changes in **E** give rise to **B** as well. That implies that **E** and **B** can exist in the *absence of any electrical charges* (i.e., no sources).
- Maxwell unified the description of electricity and magnetism and claimed that <u>light is a wave composed of oscillating **E** and **B** fields.</u> He predicted the existence of other "electromagnetic waves," which were observed by Hertz.
- Three previously distinct phenomena have been subsumed by a single theory.

Two problems for Maxwell's E-M theory

1. When an EM wave propagates through the vacuum, what is the medium? What is oscillating?
2. The equations that describe electrodynamics violate Galilean invariance. This violation should show up in the wave motion.
   Is the speed of light uniform only constant with respect to the medium?

- The medium was dubbed the luminiferous ether.
  - It was defined as being the stuff of which E-M fields are the disturbances.

Retrospective on Classical Physics

- We have now completed an introduction to the classical synthesis of physics. The common view was that in all important questions, physics was complete. Lord Kelvin, in ca 1900, made a famous speech declaring that physics was basically done, except for two little "dark clouds on the horizon":

1. Black-body radiation
2. The Michelson-Morley experiment.

- Before we encounter stormy weather, let's try to sum up classical physics and its relation to traditional philosophical questions.

The physics (as of 1900)

- Nature consists of particles and fields, imbedded in time and space.
- Elementary ingredients of the classical description:
  - Position and time are both undefined quantities. One cannot explain them to someone who does not already have a mental construct. Try to imagine a universe with two time dimensions.
  - Mass is another undefined quantity. Its *mathematical behavior* is defined by Newton's second law together with specific force laws, and some rule for measuring accelerations.
  - We still need some implicit understandings to connect all these constructs to actual experiences.
- The influence of the particles and fields on each other is described by definite deterministic equations.
- Not all the particles and fields are known.
  - There are all sorts of rule-of-thumb forces, but only G and E-M look fundamental
  - None of the detailed properties of chemistry, materials, etc., are accounted for. They might require some new field, etc. on a small scale.
- There are some unifying conservation laws:
  - Momentum, angular momentum, energy, mass, electrical charge
- There are some symmetries
  - Time translation, Space translation, rotation, mirror-image (parity),
  - Time reversal (but, oddly, only on a *microscopic* level)
  - Galilean relativity (but not for electromagnetism!)

Galilean Symmetry, explicitly

- There are rules for converting coordinates of events from one frame to another.
  - E.g. simple origin shifts: $x'=x-x_0$ or $t'=t-t_0$
  - Or Galilean transforms:
    - If two events happen at the same time in one frame, must they happen at the same time in another?
    - If two events happen at the same place in one frame, must they happen at the same place in another?

$$x' = x - vt$$
$$y' = y$$
$$z' = z$$
$$t' = t$$