Introduction to Modern Physics

So far, we have discussed physics as it was understood up to about 100 years ago.

It is sufficient to describe most of everyday life: motion of objects, heat, temperature, electricity, magnetism, light. This is all the “stuff of the industrial revolution.” Indeed it is that understanding that drove the industrial revolution.

It may have seemed to some that what could be known about physics was known, in ~1900.

But, some details remained to be understood, best classified by questions:

- How does light propagate through space?
  We now know that no medium is required but then people postulated an “ether” that was a universally pervasive medium to carry electromagnetic waves. Michelson—merely.

1887

- How is light emitted by hot objects.
  At the time, no one could calculate a spectrum that matched experiments.
- How are electrons emitted when light strikes an object? Again, at the time calculations could not match experiment.

- What are atoms actually like?
  - Where are the electrons, and where the positive charge?
  - How do electrons move in the atom to produce things like magnetism and chemistry?
  - If electrons move around in an atom, they must undergo acceleration, which we saw causes electromagnetic waves to carry off energy: electrons should radiate away all their energy. Why don't they?
  - If you remove the electrons what holds the positive charge together?

- What is the cause of radioactivity first seen in 1890's?

- What is the meaning behind the relation between $\mathbf{E}$ and $\mathbf{B}$? $\mathbf{E} = \mathbf{B} \mathbf{C}$ and "moving" charges depends on whose moving.
"Modern physics" refers to the developments since ~1900 that answer these questions (and, of course, raise more).

Note that most of the questions are driven by experiment, not a quest for some more beautiful theory. But they also involved trying to really understand what the existing theories mean.

That required quite a bit of abstraction.

Rather than just talking about force, we need to talk about fields. Light only makes sense if we have a field concept rather than just force.

Atoms and electrons are in many ways an abstraction. No one had seen one, just their effects.

This also required setting aside everyday intuition now and then.

This is important, so let's spend a couple minutes on it.
Intuition is the ability to determine something without explicit calculation. For example...

You can "sense" the speed of your car based on the relative motion of the surroundings, how much it vibrates, and how loud the wind noise is.

You can "sense" distance by comparing to known objects.

You can "sense" that something is wrong when I write down a wrong equation.

All of this is just memory applied to, hopefully, related phenomena.

If the phenomena is new, our intuition is often wrong.

E.g., \[ \frac{11}{100} \] is either obviously wrong or obviously right depending on how much intuition you have for binary arithmetic.
Another example is the Doppler shift. It may seem intuitive to us that the frequency changes when a sound source moves past, because we have heard this happen.

It is even more intuitive -- instinctive even -- for a bat.

Starfish, however, have less intuition about that and would probably think that a sound's frequency is not something that would change depending on who is listening.

We need to be careful, in studying modern physics, not to let our intuition get the better of us, or instead of being useful it becomes a bias.

We will discuss several things that seem non-intuitive. Beware.
Relativity

We saw the first pieces of relativity back in Newton's laws, when we talked about "inertial reference frames."

An inertial reference frame is one moving at constant velocity i.e., not accelerating.

For example, you sitting there are in an inertial reference frame. You can define a coordinate system with yourself at the origin and measure all points relative to your coordinate system i.e., your reference frame.

(Note that since you are rotating around the earth, sun, galaxy, etc, it is not perfectly inertial, but close enough for illustration. If necessary, imagine yourself in empty space).

You would measure the position of an object as \((x, y, z)\) in your system. Someone else, using his reference frame, would measure \((x', y', z')\) in their reference frame. Same point, just different points of view.)
This was most useful for Newton's first law, if we imagine two reference frames that are moving relative to each other.

To be inertial reference frames, they must be moving at constant velocity relative to each other i.e., not accelerating.

We said that Newton's laws apply equally in both frames, in fact in all inertial reference frames. The values (position and velocity e.g.) will be different but the laws will still apply. \( F = ma \) will still equal \( ma' \).

Let's use a specific example. I drop my keys up as I walk. You watch, stationary.

My coordinate system: is moving relative to yours at some velocity \( u \) along our common \( x \)-axes.

Your system we'll call \( S \). Mine we'll call \( S' \).
If I measure the position as a function of time, I get

\[ x'(t) = 0 \]
\[ y'(t) = -\frac{1}{2} at^2 \]
\[ z'(t) = 0 \]

where I define \( t = 0 \) as the drop time.

You measure

\[ x(t) = ut \]
\[ y(t) = -\frac{1}{2} at^2 \]
\[ z(t) = 0 \]

Assuming our origins coincide at \( t = 0 \).

We see very different motion but in both cases the motion obeys Newton's laws.

It is straightforward to define a transformation between our reference frames:

\[ x(t) = x'(t) + ut \]
\[ y(t) = y'(t) \]
\[ z(t) = z'(t) \]

\[ v(t) = \frac{dx}{dt} = \frac{dx'}{dt} + u = v' + u \]
\[ a(t) = \frac{dv}{dt} = \frac{dv'}{dt} = a' \]
An extension of this is required for \( \vec{E} \) and \( \vec{B} \) forces, of course, and that gets tricky as we saw last quarter.

If I think I'm stationary then a force on a charged particle must be only from \( \vec{E} \) in my frame, but could be due to a \( \vec{B} \) field from your point of view since the keys are moving.

We're both ok since \( \vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \) will apply in both cases. \( \vec{E} \) and \( \vec{B} \) apply just as well in both frames.

Of course, \( \vec{E} \) and \( \vec{B} \) are related to \( c \), the speed of light in vacuum, as we saw last quarter. And we can easily puzzle ourselves by changing the example from dropped keys to a light pulse, to make it simplest, imagine that I wiggle an electron around to generate a radio wave.

⇒ I'll observe an EM wave propagating out at \( v = c \).
What will you observe? $c+u$?

Obviously that gets us into trouble if $u=-c$. You'd observe non propagating light, violating Maxwell's equations.

In 1905, Einstein postulated an extension of Newton's relativity (i.e., means of describing relative motion).

Newton's approach was "the laws of mechanics must be the same in all inertial reference frames." ⇒ There is no special motionless frame.

Einstein postulated that "all laws of physics must be the same in all inertial reference frames." Again, there is no special motionless frame.

Note that the $\vec{E}$ and $\vec{B}$ symmetry is key here. Without that we could never get the laws to be the same.
Einstein's second postulate was that the speed of light in vacuum has the same value, \( c = \sqrt{\frac{1}{\mu_0 \epsilon_0}} \) in all inertial frames, that is, regardless of the velocity of the observer or the source.

This should make sense (be intuitive) in that Maxwell's equations gave us that independent of the source, and because "motionless light" is counter-intuitive.

But, they were not mainstream then. In fact, it was commonly thought that light was a disturbance propagating through some medium called the ether. This was disproved experimentally by the Michelson-Morley experiment in 1887, followed by much head-scratching.

So, we'll spend the rest of this week looking at the consequences of Einstein's postulates. These postulates can be counter-intuitive, because they deal with things moving near the speed of light which is not normally part of the everyday experience behind intuition. But they have been experimentally verified—or we wouldn't be talking about it!!
So, now suppose that instead of bouncing my keys off the floor (or, they don’t really bounce), I instead bounce light off of the floor.

\[ \Delta t = \frac{ad}{c} \]

\( \Delta t \) means in stationary (or rest) frame.

You will see this:

\[ \Delta t = \frac{2L}{c} = \frac{2}{c} \sqrt{d^2 + \left(\frac{u\Delta t}{a}\right)^2} \]

\[ \Rightarrow \Delta t = \frac{a}{c} \sqrt{\left(\frac{c\Delta t_0}{a}\right)^2 + \left(\frac{u\Delta t}{a}\right)^2} \]
solve for $\Delta t$.

$$\Delta t^2 = \frac{4}{c^2} \frac{c^2 \Delta t_0^2}{4} + \frac{4}{c^2} \frac{u^2 \Delta t^2}{4}$$

$$\Delta t^2 (1 - \frac{u^2}{c^2}) = \Delta t_0^2$$

$$\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{u^2}{c^2}}}$$

That means that "time" in one reference frame is different than in another reference frame.

To be numerically specific, suppose I were moving at $u = 0.1c$ (about 65 million MPH), then

$$\Delta t = \Delta t_0 \frac{1}{\sqrt{1-(0.1)^2}} = \Delta t_0 \left( \frac{1}{\sqrt{0.99}} \right) = 0.995 \Delta t_0$$

$\sim \frac{1}{2} \%$ difference.

If $u = 0.5c$ then $\Delta t = \Delta t_0 \left( \frac{1}{\sqrt{0.75}} \right) = \Delta t_0 \left( \frac{1}{0.87} \right)$ getting noticeable.

So, one consequence of the second postulate is that time depends on reference frame. That is not intuitive, because we have no experience moving that fast.
But, it works, and does become intuitive, once commonly experienced.

E.g. in particle physics we routinely measure sub-picosecond processes by dilating time. The decay of one type of particle (called a b-meson) occurs in about 1 picosecond. If you produce it with $u = 0.99c$, then

$$\Delta t = \Delta t_0 \frac{1}{\sqrt{1 - 0.99^2}} = \Delta t_0 \frac{1}{\sqrt{0.01}} = 7 \times \Delta t_0$$

which is easier to measure.

Note also, that orbital velocities, ~20,000 MPH are enough to produce tiny but measurable shifts.

Also note that it goes in only one direction

$$\sqrt{1 - v^2} > 1 \quad \text{so} \quad \Delta t > \Delta t_0$$

A clock is always observed to run slower in a moving frame.

Of course, neither observer can really tell who is moving -- it is all just relative motion. So it goes both ways. This may seem contradictory, so we'll have to carefully proceed...