# Introduction to modern physics

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I'm Prof Chris Done and I get to teach you this section of the course termed 'modern physics'. I got really excited about teaching this course, its my favourite bit of being an L1 tutor, that part where physics goes strange! Up till now, what you've seen has been very much built with the physical intuition you get from just looking at the world around you. But all that hard won intuition is not going to help you here, where we extend into the unfamiliar world - the world of the very fast which is special relativity, and the world of the very small which is quantum mechanics. Its not that your physical intution is wrong - it works great for the slow and macroscopic. it just needs extending when we move to more extreme environments.

What I'm going to do in both sections of this course is take you through how it works in the more extreme environment. I'll get you to build up new physical intuition by doing problems, calculating what happens. Then when you have some new feeling for how this works, I'll talk about the bigger picture, how to think like a relativist, how to think about a quantum world. But we'll get there via the maths, doing the calculations, and doing some more calculations, so you get to build up experience of these unfamiliar worlds.

Books, as ever in first year is Young and Freedman, website lecture notes as ever are on duo.

How to get help in understanding - the checklist is always:

1) yourself: read the book chapter and/or review the lecture notes/lecture capture. incidentally, lecture capture is ONLY really of use to support actually BEING at the lectures. If you disengage from us, and skip lectures thinking it'll be fine, I can always just use the videos, then you'll struggle! They are great if you are ill and need to catch up a single lecture, but don't

rely on there being time later to miss a load of lectures! there won't be.

2) google it! but beware of nutters - look at the site address and see if its reputable eg attached to a university set of lecture notes. and even then, not everything on the web (or in books) is correct.

3) your friends: you all signed the plagiarism forms, so you know what we think about COPYING. However, we DO really like you actually LEARNING from each other. Sometimes you are much better at explaining new concepts at the right level and in the right context than we are because you are comming from the same place.

4) tutorials: we have them for a reason!

5) the lecturer ie me: we can't really do quick questions after the lecture as there is generally another lecture afterwards that you have to get to and we have to clear the lecture theatre for the next lecture in this room. So instead, I'll do an open hour for the course, where you can just drop in. It'll be Tues 1-2pm in ph157 which is a small seminar room in the main physics building. But if you can't do that, just email me (chris.done@durham.ac.uk) and we can set up a time that does work.

# 1 Special Relativity (chapter 37 in YF)

The key thing in special relativity is knowing who is seeing what. Its all about constructing a reference frame for the problem. We'll do this first in 'standard' classical mechanics - called Newtonian or Galilian, and then think about how to change this once we start to think about travelling at speeds close to the speed of light.

## 1.1 Reference frames in classical mechanics: YF37.1

We can set up a reference frame using a set of axes (usually cartesian). The observer velocity is zero in their OWN reference frame. In an inertial reference frame the observer does not experience any net forces hence they are not accelerating. Inertial reference frames move at constant velocity with respect to each other.

Quantities are observed differently in different inertial frames, but absolute motion cannot be detected. eg if I throw a ball up vertically, rises, then falls. someone in an inertial frame relative to me sees this as a parabola. but its just the starting velocity that is different - we can still describe the path using $s = ut + 1/2at^2$ but just with different $u$!

For example if two observers are in inertial frames S and S' where S' moves with velocity u relative to someone in S, then someone is S' sees S move with velocity $-u$. Suppose we have coordinates $x(t), y(t), z(t)$ for some object relative to an origin at O. Then in S', with origin O' these coordinates are DIFFERENT, at $x'(t'), y'(t'), z'(t')$.

Note: prime does NOT mean derivative. It is common practice to use notation such as O and O' to denote different frames in relativity, so we will always use $df/dt$ for derivative rather than the shorthand $f'$

Coordinates of an event require a point in time as well as space - from now on the word coordinate will mean a point in both time and space - space-time coordinates - as measured in one reference frame. We can relate this to the coordinates for the same event measured in another reference frame thats moving with respect to the first with constant velocity $u$.

Lets make things simple - lets have $u$ point in the directon of the x-x' axis. And lets make their origins co-incide at t=t'=0.

Then in a Newtonian/Galiean world we can transform the spacetime positions as $x = x' + ut'$, $y = y'$, $z = z'$. But since $t = t'$ then this is $x = x' + ut$, $y = y'$, $z = z'$.

suppose instead we'd got spacetime coordinates in S and wanted to figure them out in S'. We just replace $u$ with $-u$ and primes with unprimes $x' = x - ut$, $y' = y$, $z' = z$ and of course $t' = t$.

We can use this to do velocities in inertial frames: suppose there is an object P which is moving with velocity $v'_x, v'_y, v'_z$ as measured by an observer in S'. Now lets work out what happens to its velocity as seen in S.

$$v_x = \frac{dx}{dt} = \frac{d(x' + ut)}{dt} = v'_x + u$$

$$v_y = \frac{dy}{dt} = \frac{dy'}{dt} = v'_y$$

$$v_z = \frac{dz}{dt} = \frac{dz'}{dt} = v'_z$$

we can do acceleration also

$$a_x = \frac{dv_x}{dt} = \frac{v'_x + u}{dt} = \frac{dv'_x}{dt} = a'_x$$

$$a_y = a'_y$$

$$a_z = a'_z$$

so acceleration is the same even if velocity and position is not, so Newton's laws still work - $F = ma = ma'$.

Newton First law (inertia): if no external forces are acting then an object at rest will remain at rest or if its moving it will continue to move with constant velocity

Newton Second law (acceleration): when an external force acts upon an object it will accelerate in proportion to the magnitude of the net forces and in the direction of that force. The constant of proportionality is the mass so $\vec{F} = m\vec{a}$.

Inertial reference frames are ones in which Newton's first and second laws apply. It follows that general conservation principles of momentum and energy also apply in inertial frames. any inertial frame moving with constant velocity with respect to another inertial frame is also an inertial frame.

Example: Observer sits in S at rest. sees a spacecraft move past at 1000 m/s. (so S' is moving with respect to S with velocity $+u$). The spacecraft sends out a probe whose speed is 2000 m/s relative to the spacecraft. so $v'_x = 2000$ m/s.

The observer in S sees this as moving at $v_x = v'_x + u = 3000$ m/s.

so far so obvious. whats the catch?

The catch is light. Maxwells equations says light travels at the speed of light! but doesn't say relative to anything.

so now, instead of launching a probe, the spacecraft turns on a searchlight which travels at speed $c$ relative to the spacecraft. Classical mechanics says the observer in S should see this at speed $v_x = c + u > c$. Maxwells equations says it travels at $c$.

So something doesn't work. Either there is such a thing as a special inertial reference frame in which Maxwells equations work. Perhaps space is filled with something - and aether - in which electromagnetic waves propagate? Or maybe velocities don't add up the way they should in classical physics....

So one way to test this is to look. The Michelson-Morely experiment took the idea of an aether and figured out that the motion of the earth means that an experiment would move with respect to this aether. so we could detect motion relative to the frame of the aether by looking at the speed of light.

This would mean that the laws of physics were NOT the same in all inertial frames, but that there was a special frame for electromagnetism, the frame of the aether.

So they did an interferometer, with axes at 90 degrees. The earth moving with respect to the aether means that they should see a shift in the interference when they rotated it. They didn't.

there is no aether/special inertial frame for light. Maxwell is right, its classical physics which is wrong.