Magic of physics: Summary notes

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1 Week 1

a. Introduce yourselves. Play the name game. Ask each student to introduce him/herself, state his/her area of study, and give one interesting fact about him/herself. You can do the same. Encourage everyone to ask questions. Our taxes are paying for the tutorials! Ask if anyone has questions about the basic quantities (speed, velocity, acceleration, and momentum) we use to quantify motion. Are their any specific questions about the lectures? In my opinion, it is reasonable to spend as much time as needed clarifying the students' puzzles. You do not have to cover all of the following.

Ask your students to list the three most important ideas from the lectures and then rank them in order of significance. [1. Scientific method, 2. speed, etc., 3. Conservation of momentum.]

b. Is it fair to idealize the universe as Galileo did by ignoring air resistance? Yes, we are always simplifying things as far as we can. We make progress by building on earlier models. The fine details are often ignored, at least initially. The Earth is a sphere flattened at the poles and is not smooth. But we often pretend that it, the other planets, and the Sun are perfect spheres with all of their mass concentrated in their centres. The equations are easier to solve in a simple model. The basic principles are more comprehensible. If our model is too simple and does not agree with observations, then we have to revise our theory.

c. How do we view friction and air resistance? A force is a pull or push. Friction and air resistance are forces that act in the direction opposite to the motion of an object. Friction is due to the contact between an object and a surface. No surface is perfectly smooth. There are microscopic hills and valleys on the surface of every object. Air resistance is due to molecules pushing against a moving object. It is the friction of air molecules in contact with a moving object.

We view friction and air resistance as forces. In certain situations they can be reduced or are totally absent.

Q: Air resistance on an object is independent of the speed of the object. (a) True (b) False [(b) False - Think about what you feel on your hand as you move it through the air.]

d. Here is a conceptual question that I used in PHY131. You can try it out in PHY100. Write the question and draw pictures of cars on the board. After a minute or two, ask the class to vote whether the answer is A or B. Discuss why the solution is Car B.

Which car is going faster, A or B? Assume there are equal intervals of time between the frames of both movies.

DRAW PICTURES OF THE CARS!!

e. How important is the idea that physical quantities are conserved?
It appears in much physics. It helps us figure out how systems behave without relying on detailed solutions of Newton's equations of motion.

Wednesday tutorials: DASH depends on an object's mass and velocity. (Momentum).

1.1 Summary of week 1

In physics, knowledge is acquired by observing a phenomenon or by doing an experiment. A theory is developed to explain the above observations. Repeatable, controlled, and precise experiments are performed to test the theory. If there is a disagreement between the experiments and theory, the original theory is revised and more experiments are undertaken.

- Mechanics is the study of motion. The metre (m), second (s), and kilogram (kg) are the standard units for measuring position, time, and mass, respectively. An object's speed, velocity, acceleration, and momentum are used to quantify its motion. These quantities are defined as

  speed = (change in position)/(change in time) velocity = the speed of an object and its direction of motion, acceleration = (change in velocity)/(change in time), and momentum = (an object's mass)x(an object's velocity).

- The symbols / and x mean divide by and multiply by, respectively.

- Newtons laws of classical physics were the bedrock of physics for over 300 years. They are:

- Newton's First Theory (Law) of Motion An object moves with constant velocity unless it experiences an external force. A force is a push or a pull.
- Newton's Second Theory (Law) of Motion An object's acceleration a is given by a=Fnet/m, where Fnet and m are the net force on and mass of the object. The net or total force is the sum of all the forces acting on the object. If the total force, mass, and the object's position and velocity at some time are given, then the object's position and velocity at any later time can be specified. The equation a=Fnet/m, or equivalently Fnet=ma, is solved to find the path followed by the object using calculus and the object's initial conditions which are its initial position and velocity.
- Newton's Third Theory (Law) of Motion For every action force there is a reaction force that has the same size or magnitude as, but points in the opposite direction to, the action force. These forces act on different objects.
- Distinguish between vectors and scalars.
- A force is a push or pull (HOW MANY FORCES ON A BOOK). Suppose a system consists of many objects. Add the momentum of each object to give the total momentum for the entire system. The total momentum remains constant at all times if there is no total external force on the system. This is known as the conservation of momentum. The total momentum of the system remains the same at all times.
- Circular motion - how does it feel to around a roundabout. Is it accelerated motion

Tutorial quiz - What is the standard unit for measuring time? (second).

2 Week 2

2.1 Review last week

- Discussed what a scientific framework is and we can make progress with it.
- Is there a well defined definition of science? Does it (the Popper-Falsifiability view) need changing?
- Definitions of velocity, speed, position and distance

2.2 Newtons laws

Newtons laws of classical physics were the bedrock of physics for over 300 years. They are:

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- Newton's Second Theory (Law) of Motion An object's acceleration a is given by a=Fnet/m, where Fnet and m are the net force on and mass of the object. The net or total force is the sum of all the forces acting on the object. If the total force, mass, and the object's position and velocity at some time are given, then the object's position and velocity at any later time can be specified. The equation a=Fnet/m, or equivalently Fnet=ma, is solved to find the path followed by the object using calculus and the object's initial conditions which are its initial position and velocity.
- Newton's Third Theory (Law) of Motion For every action force there is a reaction force that has the same size or magnitude as, but points in the opposite direction to, the action force. These forces act on different objects.

Fist lets start with making sure we understand the definitions -

- Acceleration - This is the quantity that changes when a force acts on a system and appears in Newtons laws. Acceleration is how quickly an objects' velocity changes with time. Mathematically,

$$a = \frac{\Delta v}{\Delta t} \tag{2.1}$$

  where a is the acceleration, Δv represents the change in velocity of an object, Δt is the time it takes for the velocity to change by Δv.

- Momentum - Mathematically it is defined simply as the mass of an object multiplied by its velocity

$$p = mv \tag{2.2}$$

  where p is the conventially used letter for momentum, m is the mass and v is the velocity. An important thing to know is that momentum is conserved in a system in which there are <u>no external forces</u> on the system.

Ask your groups of students to answer these conceptual discussion questions.

Q: The expressions $a = F_{net}/m$ and $F_{net} = ma$ are mathematically equivalent.
(a) True. (b) False. [(a)]

Q: Why write Newton's Second Theory (Law) as $a = F_net/m$?

(a) It relates a and F_{net} in a clearer manner. (Apply a force and observe the resulting acceleration.) (b) It gives the mathematicians something to think about. (How many ways can a mathematician rewrite an equation?)

Q: Which undergoes a greater change in momentum during its collision with the floor, a piece of paper or a coin?
(a) The piece of paper. (b) The coin. [(b)]
b. Newton formulated his Theory II as F=(change in momentum)/(change in time). Do not forget that momentum and force are quantities that have directions. This is equivalent to $F_{net} = ma$, if the mass of the object is constant. You do not have to show this mathematically, but you could experimentally. A piece of paper does not have much mass. Allow it to fall to the floor. When it hits the ground with velocity v, its momentum changes from mv to zero. This results in a force applied to the ground. In comparison, a quarter has more mass (M) and will hit the ground with a greater velocity (V). Its momentum change upon striking the floor will be MV. This results in a larger force applied to the ground assuming that the change in time is the same in both cases.

Q: A car travels at constant speed in a circle. The car moves with
(a) constant velocity. (b) constant acceleration.
(c) none of the above. [(c) - the acceleration direction changes.]
c. Why is circular motion an example of accelerated motion? If you go at constant speed in a straight line, then your velocity vector does not change with time. Your acceleration is zero. You do not feel a force pushing you back in your chair. Ignore the potholes in the road. If you go at constant speed along a curved road, then the length of your velocity vector does not change, but its direction does. This results in an acceleration towards the centre of the curved road. You feel the car wanting to move towards the centre of the curved path. Draw some pictures for the two cases. In the curved road situation, draw a circle and two tangential velocity vectors v1 and v2 at two different times along the path. Add the vectors v2 + (-v1) and demonstrate that the change in velocity points towards the centre of the circle. Since acceleration = (change in velocity)/(change in time), the acceleration and the force (F=ma) are centrally directed. This is important to our understanding of planetary motion.

d. Q: The air resistance on an object depend on the object's speed. (a) True. (b) False. [(b) - True. Demonstrate this by moving your hand through the air.]

Wednesday tutorials: For every $-----$ force, there is an $-----$ and opposite reaction force. (action, equal)

3 Week 3 - Newtonian gravity and energy

3.1 Review of last week

We discussed Newtons laws of motion. Easy way to remember them is;

- First law tells us things stay in constant motion unless external forces act.
- Second law tells us how motion changes under the action of forces. (Remember the definition in terms of change in momentum is more general)
- Third law tells us that for every force that causes motion there is an equal and opposite force on the force causing the motion.

3.2 Newtonian gravity

Last week we touched a bit on Newtonian gravity - this week we discuss it in more detail.

Newtonian gravity describes how massive objects (i.e objects that have the property of "mass" as we discussed previously) exert forces on each other. Consider two massive objects of mass M and mass m - the gravitational force F_g between them is given by

$$F_g = \frac{GMm}{r^2} \tag{3.1}$$

where G is Newton's constant of gravity (its just a number) and r is the distance between the two objects (DRAW A DIAGRAM!).

Gravitational forces are always attractive - that makes them different from the other forces (and also makes it very strange in many different contexts).

3.3 Energy

Energy is a physical objects ability to do work (technical definition is too advance for this course). Energy is a conserved quantity in physics- i.e the total energy of system doesn't change with time. This allows us to use this quantity to do calculations in physics.

There are two types of energy:

- Kinetic energy - The energy stored in motion. If a particle is moving it has some energy known as kinetic energy.
- Potential energy - The energy that is stored in a interacting force. There are four types of fundamental potential energy - Gravity, Electromagnetism, Strong force (Yang mills) and Weak nuclear force. We will only talk about two of these.

The usefulness and difference between KE and PE is best illustrated from an example.

DRAW DIAGRAM OF OBJECT FALLING FROM BUILDING.

Then talk about letting the particle go at a tangential velocity and relate it to how orbits form.

3.4 Conceptual questions

a. Why do the planets not fall toward the centre of the Sun? The gravitational force on a planet due to the Sun is directed towards the centre of the Sun. A planet does not directly fall into the Sun since it has enough tangential velocity to keep it in an elliptical orbit. The tangential velocities were established when the Solar System formed. Billions of years ago, the cloud of material that collapsed (condensed) to make the Sun and the planets was rotating. This rotational motion is maintained (conserved) to this day by the Sun rotating about its axis and the planets orbiting around the Sun. Remember that objects want to move with uniform velocity (straight line with constant speed) unless they are acted on by an external force (Theory I). The planets want to go "straight", but they get "pulled down" by the Sun's gravitational force. An elliptical orbit indicates that a planet is experiencing a nonzero net force.

b. If everything with mass exerts a gravitational force, then why do we observe approximately elliptical planetary orbits? The Sun is much more massive than and therefore exerts the largest gravitational force on the planets. It is true that the net force on a planet is due to the sum of all of the gravitational forces acting on it. For example, the Earth also feels the forces of the Moon and the largest planet Jupiter. The Moon's force results in a wiggle in the Earth's path. Jupiter is much lighter than the Sun and far away from us, so that $Fg = GMm/R^2$ is small. The effect of Jupiter on planets such as the Earth accumulates over many years.

Q: You can draw a picture of the answers. Mars follows an elliptical orbit around the Sun. The acceleration of Mars is directed (a) toward the Sun. (b) away from the Sun. (c) along the direction of its velocity (tangent to the ellipse). [(a)]

Q: This is related to the space probe Rosetta landing on Comet 67P. Ask if your students understand the words elongated elliptical orbit. Most comets in the Solar System follow elliptical orbits that are more elongated than those followed by the planets. This has occurred since (a) the Sun's gravitational force is smaller on a comet than a planet. (b) the Sun's gravitational force is greater on a comet than a planet. (c) comets and planets have different initial conditions. [(c) - According to Newton's Second Theory, the initial position and velocity at some earlier time affects the motion of an object at later times. When a ball is launched at a larger compared to smaller angle to the ground, the path the ball follows is narrower or wider. The initial conditions associated with the creation of comets and planets resulted in these object's moving along ellipses with different elongations.]

The above solution is what we are expecting for the typical Homework Question or Final Exam problem.

Q: An object is dropped from rest from the top of the McLennan Physics Laboratory. The system initially has (a) potential energy. (b) kinetic energy. (c) potential and kinetic energy. (d) no energy. [(a) - It has potential, but no kinetic, energy due to the location of the object relative to the Earth. The object and the Earth exert forces on one another.]

Q: The above object is falling to the Earth. Just before it hits the ground, the system has (a) potential energy. (b) kinetic energy. (c) potential and kinetic energy. (d) no energy. [(c) - The system has potential and kinetic energy. The object is in motion and is at a certain position relative to the Earth.]

3.5 Tutorial quiz

Kinetic energy is associated with an objects —— (motion or speed squared).

4 Week 4 - Electric charge

4.1 Review of last week

Last week we talked about Newtonian gravity and energy.

- Newtonian gravity tells us that two particles which have the property of mass will feel an attractive force between them. The formula for that force is

$$F_g = \frac{GMm}{r^2} \tag{4.1}$$

- There are two types of energy: Kinetic energy (the energy related to a particles motion. And Potential energy related to the particles ability to do work (as we will see today this actually comes from the energy stored in the fields accounting for the force).

DRAW SKETCH OF PARTICLE FALLING FROM BUILDING.

4.2 Introduction to electricity

Electric charge is a property that some particles in nature have. From example the most familiar particle with this property is the electron. It is the particle that moves in the wires around us and we call this movement electricity. What is another property that particles have (that we have talked about previously)? Mass. And we know that Newton gave us an equation that tells the force felt by two massive particles

$$F_g = \frac{GMm}{r^2} \tag{4.2}$$

Similarly there is a force between two electrically charged particles

$$F_e = \frac{qQ}{4\pi\epsilon_0 r^2} \tag{4.3}$$

This is called the Coloumb force. Note the similarity in their form. But there are key differences between the gravitational force and electric force. What are they?

- The most important one is that the force of electricity can be both positive and negative. In the sense that a particle can have a negative electric charge or a positive charge. Positive charge will repel another positive charge. Whereas negative charge will attract a positive charge.
- The electric force is much stronger than the gravitational force. Think about it. It takes the entire earth to pull you down to the floor. But a much smaller magnet (which is related to the electric force) can attract you with the same force.

4.3 Introduction to fields

There has always been some unease in physics with the concept of force. This is because the force seems to act instantenously across a large distance. From special relativity we know nothing can travel faster than the speed of light. So how do reconcile both these concepts? The idea that solves this problem is that of a field. The idea of a field is best described by a sketch (DRAW STATIC ELECTRIC FIELD WITH FIELD LINES ETC). So the field is thought of as a physical object that has some value at each point in space and time and then we describe the dynamics of particles in terms of this field. This idea was first developed by Michael Faraday with regards to electric fields (in modern physics all fundamental forces are written in terms of fields). So we can describe the force felt by a particle of charge q by

$$F_e = \vec{E}(x)q \tag{4.4}$$

4.4 Magnetic fields

Magnetic fields are generated by motion of electric charges. They depend on the velocity of the charge on the magnitude of the charge. DRAW SKETCH OF MAGNETIC FIELD LINES FOR BAR MAGNET.

4.5 Conceptual question

Q: Is the nucleus of an atom is unstable due to the electric force between protons? (a) Yes. (b) No. (c) Maybe. [(a)]

I defined the nucleus as consisting of protons and neutrons. According to the basic experiments mentioned above, since protons have the same electric charge, they should repel one another. The nucleus should not remain as a single unit. Someone felt that there are electrons in the nucleus, but that is not a part of the question or the definition of a nucleus. Someone said there are gluons which bind the protons. This is fine since it illustrates how physics progresses. EM theory says that a nucleus should explode which makes us wonder if there is another force which can bind the nucleons. But the question has nothing to do with the strong force.

b. When we say that an object is charged, we mean that it contains more positive than negative charges or vice versa. A charged object, whether it is stationary or moving, produces an electric field.

Q: The expression $Fe = qE$ gives the electric force on an object with net electric charge q due to an electric field E that is due to (a) the object. (b) sources external to the object. (c) the object and sources external to the object. (d) magic. [(b)]

Q: An object with net negative electric charge q is subjected to an electric field E that points to the right −¿. In which direction does the electric force on the object point? (a) −¿ (to the right). (b) ¡− (to the left). (c) $^{(}up$). (d) V (down). (e) The force is zero. [(b) - Since q is negative and E is to the right, Fe=qE implies that the electric force is to the left.]

c. What is the origin of magnetism? Since there are no isolated magnetic poles (monopoles), all macroscopic magnetic fields are due to the motion of charged particles or the intrinsic quantum property of particles called spin. The spin of an electron plays a role in creating permanent magnets. You do not need to emphasize the concept of spin at this time. It will be examined later in the course. A changing electric field produces a magnetic field.

Q: A changing electric field at a point P in space means (a) the magnitude of the electric field changes at P. (b) the direction of the electric field changes at P. (c) (a) and/or (b). (d) none of the above. [(c)]

A "changing electric or magnetic field" means a time-dependent electric or magnetic field at a point in space. The magnitude and/or direction of the field vary with time. If the charges in a wire on average move in one direction at constant velocity, then a steady magnetic field B is created outside of the wire. The magnetic field lines consist of circular loops. The direction of the field lines can be specified by the right-hand rule. Place your thumb in the direction of the electric current. The way your fingers curl around the wire gives the direction of B.

d. How does a bar magnet work? In most materials, the positive nuclei are essentially fixed. They oscillate a little about their equilibrium sites. Some of the negative electrons have more freedom to move around. For most materials, the free electrons are not travelling in an organized way. The magnetic fields due to the motion and the spins of the electrons are randomly oriented. The intrinsic spin of an electron produces a magnetic field that looks like that of a bar magnet. Field lines in a normal vs. magnetic substance:

/ — — vs. — — — — / — — — —

Each line should end with an arrow. On the left, the arrows point randomly. On the right, each arrow points in the same direction.

For some materials, such as iron and nickel, the motions of the electrons are more organized. The electrons circle around each nucleus in the same way and their spins are aligned. The magnetic fields due to these electrons point in the same direction. The total of these small fields is a macroscopic permanent field. The field lines do not stop or end at the N or S pole of a bar magnet. The field lines extend through the magnet. They make big loops analogous to those around a current carrying wire. (Did you know that you can destroy a permanent magnet by hitting it or heating it?)

4.6 Tutorial quiz

An electric field has a size and a ——-?

5 Week 5

5.1 Review of last week

- Coloumb force law
- Like charges repel and opposite charges attract (Draw diagrams)
- Introduction to field (electric and magnetic)

Review of magnetism - How does a bar magnet work?

In most materials, the positive nuclei are essentially fixed. They oscillate a little about their equilibrium state. Some of the negative electrons have more freedom to move around. For most materials, the free electrons are not travelling in an organized way. The magnetic fields due to the motion and spins of the electrons are randomly oriented. The intrinsic spin of an electron produces a magnetic field that looks like that of a bar magnet. (DRAW SPINS ALIGNED MAGNET AND MISALIGNED NON MAGNET).

5.2 Maxwell's equations!!

There are the first unified set of equations in physics. Their importance cannot be overstated. Relativity follows from them. Gauge theory follows from them. Basically they are the foundation of modern physics. Since they are so important I will write them down!

- 1) The relation between electric charges and electric fields.

$$\nabla.\vec{E} = \frac{\rho}{\epsilon_0} \tag{5.1}$$

- 2) Magnetic field lines form loops. There are no magnetic monopoles.

$$\nabla \cdot \vec{B} = 0 \tag{5.2}$$

- 3) A changing magnetic field (in time) produces an electric field

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{5.3}$$

- 4) An electric current produces a magnetic field. A changing electric field (in time) produces a magnetic field.

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \tag{5.4}$$

  Equations 1 and 2 indiciate that the electric and magnetic fields look like different beasts. Whether an electrically charged object is at rest, moving with constant velocity, or accelerating, it has an associated electric field. A charged object never loses its electric field. If a charged object is moving relative to an observer at constant velocity, the observer can measure a magnetic field, as well as an electric field. Nevertheless E and B are closely related as indicated 3 and 4.

  According to these equations there is a self-perpetuating pattern of E and B fields called an EM wave. Once EM waves are produced by accelerating charges they no longer depend on the motion of the source. They lead a life of their own.

5.3 Introduction to waves

Draw a periodic sinusoidal wave and indicate the wavelength (lambda) and amplitude (A). Define the frequency (nu). The wave speed can be shown to be v=wavelength*frequency=lambda*nu. The energy of a wave is proportional to its amplitude squared.

Define two types of waves and give examples of sound waves.

5.3.1 Tutorial quiz

Wednesday tutorials: An —– wave consists of a pattern of —– and magnetic fields. (electromagnetic, electric)

6 Week 6 - Double slit expriment

6.1 Review of last week

- We introduced the concept of a wave. (Oscillating pattern)
- Draw a sine wave and denoted what the wavelength, frequency, amplitude and speed of the waves are.
- Two types of waves. Longitudinal and transeverse (light and sound).

6.2 Double slit experiment

Draw interference pattern from double slit experiment.

- An important property of waves is that they can be added together or superimposed to produce new waves.
- A superposition that results in a larger amplitude wave is called constructive interference. A superposition that results in a smaller amplitude wave is called destructive.
- The interference pattern seem from water waves (from making a source that oscillates in the water) is the same as what is observed from EM waves and this gives.
- If the slits are large compared to the wavelength then the waves ho through each slit without much spreading (diffraction). You will only see two seperate bright fringes or bands at the detector.
- Each fringe will have an intensity (energy) proportional to A^2, where A is the amplitude of the wave originating from each slit.
- For light in free space the intensity is proportional to E^2, where E is the amplitude to the electric field.
- In order to the see the bright-dark pattern of fringes at the detector, the slights have to small compared to the wavelength in the waves.
- Q) If the wave originating from each hole in the double-slit experiment has an amplitude A, the amplitude of the superposed wave at a bright fringe is $\underline{\mathrm{2A = A + A}}$
- If the wave originating from each hole in the double-slit experiment has an amplitude A, the intensity (energy) of the superposed wave at a bright fringe is proportional to $(2A)^2 = 4A^2$.
- If the wave originating from each hole in the double-slit experiment has an amplitude A, the amplitude of the superposed wave at a dark fringe is $A + (-A) = 0$.
- If the wave originating from each hole in the double-slit experiment has an amplitude A, the intensity (energy) of the superposed wave at a dark fringe is proportional to $0^2 = 0$

6.3 Reflection of waves - greenhouse effect

So far a lot of what we have talked about is waves diffracting. But waves can also reflect of materials. For example carbon dioxide can relflect light (in the infrared spectrum) back towards the Earth. Water vapour can do the same.
Give example of Venus.

6.4 Motion of light clocks

Explain that light travels at a fixed speed as seen by all obsevers as was seen in Maxwell's equations.

Draw a light clock. Then draw it moving to the right with some velocity. Explain why the stationary observer will see the clock tick slower.

6.5 Tutorial quiz

Waver vapour can —— infrared radiation toward the Earth's surface.

7 Week 7 - Introducing special relativity

7.1 Review of last week

Last week we talked about the double-slit experiment. The key ideas were the following:

- The amplitudes of two (or more) waves can be added. This is known as the superposition principle and hold for many physical systems (that have linear wave equations).
- One way the waves can add is constructively, i.e the amplitudes of the waves add up (I also told them about how this means the waves are in phase). This is where the bright fringes are seen in the double slit experiment
- The other way is destructively - when the amplitudes are equal and opposite and therefore cancel out. This is where the dark fringes are in the double slit experiment.

7.2 Postulates of special relativity

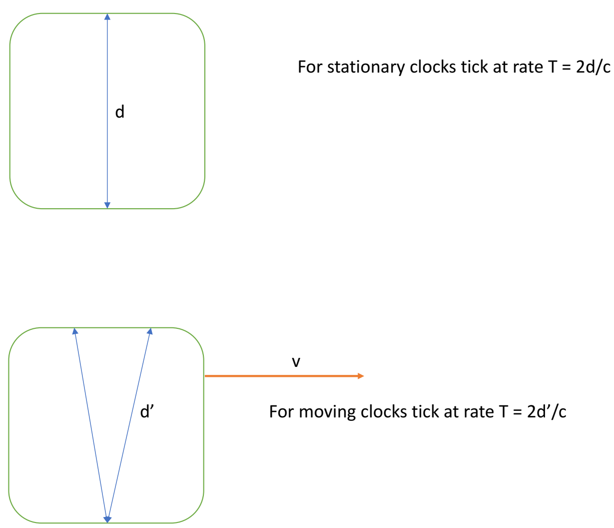

Figure 1: A light clock is a box that has a laser (or anything that emits light) on the top. The light gets emitted and reflects of the bottom of the box and comes back to the top. Once the light reaches the top, there is a "tick". These ticks represent the time. For a stationary observer looking at a stationary clock he sees that time at which the ticks happen is $T = 2d/c$. But if the clocks start moving and the observer is stationary the ticks are now at $T = 2d'/c$. It is easy to see that the d' is greater than d and therefore as the observer standing stationary sees it, the ticks of the clock take longer. Which is what we mean when we say that time is going slower for the moving body as seen by a stationary observer. The reverse is also true of course. As the clock (or an observer sitting with that clock) "sees" our (the stationary observers) clock (the watch on your wrist), it will also see our clock slow.

The key ideas (postulates) of special relativity are

- The speed of light is the same as seen by all observers.
- The laws of physics are the same as seen by all observer moving at fixed velocity.

The ideas follow from Maxwells equations. They are not just postulated without any reason.

7.3 Moving clocks

If you just follow these postulates of special relativity to their logical conclusions you learn some very strange things.
One of the conclusions you draw is that their is no universal concept of time. Time is relative. It is relatively simple to see why using the idea of a light clock (you may want to explain that this is only real way to measure time). I explain the idea of a light clock in figure 1, the caption has all the explanation.[1]. We will come back to light clocks when we discuss spacetime diagrams .

- The change of time depending on the velocity of observers is characterized by a factor γ (sometimes called a boost factor or Lorentz factor or the gamma factor).[2]

$$\gamma = \sqrt{\frac{1}{1 - v^2/c^2}} \tag{7.1}$$

- The effect of time slowing down as seen by stationary observers is known as time dilation. The time of a stationary observer T is related to the time T' of an observer moving with velocity v by

$$T' = \frac{T}{\gamma} \tag{7.2}$$

- There is an analog of time dilation in terms of space, or lengths of objects as well.[3]. An observer moving with velocity v w.r.t to a stationary observer is holding a metre stick of length L and as the stationary observer sees it, the length is L

$$L' = \gamma L \tag{7.3}$$

  So the stationary observer sees the moving length become shorter. This is known as length contraction.

7.4 Spacetime

- Using length contraction and time dilation SR motivates the notion of spacetime. The idea behind spacetime is that neither space (i.e the three dimensions you see) nor time make sense by themselves. The only physical thing is some combination of the two (the metric, but don't discuss that with them yet, since I think it will just confuse them) and this is what spacetime is.

[1] I would spend as much time as you feel necessary on the light clock. I think the students who get a hang of the light clock get a better understanding of SR.

[2] They don't need to know the equations but I do write down the important ones that are relatively simple to explain since some them can follow simple equations.

[3] I'm not sure whether its worth doing a thought experiment for this as well. It depends on how your doing for time. But if you want to motivate length contraction then you can do the thought experiment of carrying a metre stick and moving at velocity v w.r.t to a stationary observer. Since both you and the person moving must agree on the speed of light, as you see the stick it must appear smaller since light has to cross a smaller distance (and the way you measure the distance is by seeing a light ray moving for a certain amount of time. And you know the time T' on the moving person, as you see it, is slower than your clock, so the distance must be smaller). This is just the way I explain this, you can of course give any explanation you want

- It follows from the equations of SR and the idea of spacetime that mass and energy have to be related[4]. They are related by the famous equation.

$$E = mc^2 \tag{7.4}$$

  where m is the mass of an object at rest. Of course, in general, the energy of an object also depends on its motion. That's the kinetic energy. Therefore the total energy is the sum of the rest energy (mc^2) and its kinetic energy ($1/2mv^2$) and any potential energies from external forces.
- This equation has profound implications. It tells us that any matter will have a energy associated with it. In particular, since c^2 is a very big number, small amounts of matter have a very large amount of energy in them. This is how the atomic bomb was created.

7.5 Tutorial quiz

An object's total energy depends on its mass and ———?

[4]I don't even try to motivate this because I have no idea how to motivate it in any heuristic way

8 Week 8 - Introduction to General relativity

8.1 Review of last week

Last week you learnt about special relativity, SR. The postulates of SR were

- The speed of light is the same as seen by all observers.
- The laws of physics are the same as seen by all observers moving at a fixed velocity (inertial observers).

The key ideas that come from these postulates are:

- There is no universal concept of time. Time is relative.
- Space and time have no physical meaning. The only physical object is some combination of the two (the metric, but they haven't been introduced to that yet).
- We also get the famous equation

$$E = mc^2 \tag{8.1}$$

8.2 Introducing GR - Equivalence principle

The starting point of general relativity is surprisingly simple. It is a thought experiment.[5]

- Suppose your in an elevator in space. If there is a rocket attached to the bottom, then when the rocket pushes the elevator up you will feel a force on your feet. This force is due to the acceleration caused by the rocket.
- Now suppose your in an elevator on the earth. The elevator doesn't move, but there is gravity to pull you down.
- Einstein realised that there is no way distinguish by standing in an elevator (and you have no access to anything outside the elevator) whether you are in an elevator that is accelerating up (at the same rate as gravity) or in a stationary elevator in the presence of a gravitational field. He called this his "happiest thought"

He proposed the generalised principle: Uniform acceleration is the same as a constant gravitational field. This is known as the equivalence principle.

8.3 Weightless-ness

This means that if we are in a constant gravitational field, then we can accelerate in such a way to "remove" the force of gravity. For example, if you are in a plane and it starts to drop down at the same rate as the earth's gravity pulls you down, then you don't feel gravity. You feel weightless.

This is exactly how astronauts in space feel weightless. You might need realise, but things that orbit the earth like the moon and the ISS are actually falling/accelerating towards the earth. The

[5] I would spend as much time as you think is necessary so that the students really appreciate this thought experiment. I think if they can get there head around this, they should have a better appreciation of what GR is. You can draw some sketches on the board to elaborate further.

acceleration is exactly the same as the gravitational attraction. This is why the astronauts inside them feel weightless.

The movie gravity has a part in which the astronauts hair are not floating while she is in space. This would't happen if they were in space - in space the hair would just float since she should not be able to feel the "force" of gravity. It just shows that the movie was shot on the earth.

It is important to emphasise what the equivalence principle tells us, since it is confusing when you first think about it.

- It doesn't tell us that gravity doesn't exist.
- It tells us that "locally" (i.e inside an elevator where you don't have access to external objects) you can remove the force of gravity by going into an accelerating frame.
- It also doesn't mean acceleration is the same as gravity. This is only true when you have a constant gravitational field. Gravity is in fact the opposite of this.
- It makes an important (mathematical) statement that any gravitational field, when looked at on a "sufficiently small" distance scale, must be the same as an accelerating frame.

8.4 So what is gravity? Long stick man in gravitational field.

So far we have discussed what the equivalence principle is and how it is similar to acceleration. But what is gravity if it is not the same as acceleration? Can anyone think of what happens to an object in a non-uniform gravitational field?

The best way to think about it is to draw a very long stick man next to a heavy object. The stick man will feel a different force of gravity on its head then on its feet and will therefore feel a tidal force. This tidal force will stretch out the stick man. An accelerating reference frame cannot do that. Thus the essence of gravity is tidal forces. This is the same tidal force that causes the ocean to bulge up and cause the tides here on earth.

8.5 Curving of spacetime

Using the equivalence principle and special relativity (and ten years of hard work! with a lot of friends from great mathematicians) Einstein came up with General relativity. In GR, spacetime takes centre stage. In special relativity we learnt that neither time nor space by themselves have any physical meaning.

- Spacetime is a four dimensional (3 dimenions of space and 1 one time) physical object.
- In GR it is a real thing with properties just like any other thing like a pencil or a piece of paper.
- GR tells us that gravity is not a force, but it is actually the curvature of this physical object called spacetime.
- Spacetime changes its curvature depending on the matter that is within it.
- Objects move through spacetime. The trajectories (motion) of objects in spacetime depends on how it is curved (which is determined by the matter in it). For example, a tennis ball will move differently in a spacetime that is "flat" then in a spacetime that is slightly "curved", for example a sphere. (You can use the standard curving of paper to demonstrate this if you like).

– Objects and light (photons) follow geodesics in spacetime. In flat space geodesic is just a straight line. In general, a geodesic is a line that has the shortest interval in that space. For example the surface of a sphere - the geodesics are lines on longitude.

8.6 Tutorial quiz

——- and light move along geodesics in spacetime?

9 Week 9 - More general relativity

9.1 Review of last week (or two)

- Introduction to special relativity - everyone understand the concepts of spacetime, speed of light being constant, lightclock, time dilation, length contraction. (DRAW SPACETIME DIAGRAM).
- Introduction to general relativity - everyone understand the idea of equivalence principle, relation between inertial mass and gravitational mass. Gravity is all about tidal forces. (DRAW STICKMAN IF NEEDED)

9.2 Doppler effect

The measured frequency and wavelength of waves depends on the motion of the waves' source relative to an observer. Consider the sound emitted by an amulance's siren (Draw image of stretching of waves)

- Ambulance moving *toward* you will have its frequency *increase*.
- Opposite for the ambulance moving away from you.
- The speed of the waves is determined by the atmospheric conditions.
- This same effect happens with light.
- A star that is stationary and emits light at a fixed frequency will appear to emit at a higher frequency if its moving towards us. This is known as a *blue shift*
- Hubble used this to show that the universe is expanding as all the stars are moving away from us (redshifting away)
- This *does not* imply that we are the centre of the universe.

9.3 Gravitational waves

- So you have learnt about spacetime.
- Spacetime is actually a physical thing. It is infact a field, just like the electric and magnetic fields are. It is a tensor field and has 10 components!
- The spacetime field can fluctuate in the same way an EM field can.
- An EM field fluctuating is called EM radiation or light. A fluctuation (wave) in the spacetime is known as a gravitational wave.
- An accelerating charge in EM emits light. An accelerating massive object emits gravitational waves.
- A gravitational wave is literally a change in space and time.
- Gravitational waves also travel at the speed of light.

The way gravitational waves are measured is by measuring the change between two particles (ideally they should be free-falling particles). This was first done by LIGO last february! The deviations are of the order of 10^{-18}.

9.4 Black Holes

Draw a schematic of black hole and label its event horizon.

- How does a black hole form? In general its from a star collapsing under its gravity (once it doesn't have enough fusion energy).
- The characteristic of a black hole its event horizon. Its a spherical shell and beyond it spacetime is accelerating towards the centre of the black hole quicker then light can escape.
- What happens beyond the horizon is not known.
- Classically a black hole is described by only three numbers- its mass, charge and angular momentum (how quickly it is rotating).
- At the centre of a black hole GR breaks down as spacetime seems to have infinite curvature.

9.5 Tutorial quiz

The acceleration of objects produces − − − − − − − − − − waves.

10 Week 10 - Photoelectric effect

10.1 Introducing a black body

- A key object in classical physics is a blackbody. It is an object that absorbs all the EM radiation incident upon and then emits radiation. There are no perfect black bodies in nature. In fact one of the best known objects that is a black body is the entire universe (CMB).
- As an example you can think of a metal element on an electric stove as a black body.
- There was a problem with this description in classical mechanics. The issue was that if all of the wavelengths of lights could carry energy in the black body, since the wavelengths are continuous, the energy they emit should be infinite! But of course this cannot be true. The solution turned out to be quantum physics.
- The idea that Einstein came up with and won the noble prize for, was the photoelectric effect. In which he basically outlines that light has to come in discrete packets with DISCRETE wavelengths, $E = \hbar\omega$.
- DRAW METAL AND PHOTOELECTRIC EFFECT (next section)
- This also solves the infrared catastrophe. Since not all wavelengths can be excited.

10.2 Photoelectric effect

  - The electrons in a piece of metal are trapped. If they are given energy they can be liberated.
  - In the photoelectric, a photon of a frequency greated than the energy needed for the electron in it can excite the electron. This then leads to a current that is detected. Note that shining more photons, i.e more intensity, doesnt have any effect on the current. Only the increase in frequency (i.e the color of the light) can make a difference.
  - This is in contradiction to classical phyiscs, which predicts that the energy of the light is proportional to the wave amplitude squared.

10.3 Atomic structure

This same fact that energy comes in quanta also explains why electrons travel in fixed orbits around an atom (quantized angular momentum, Bohr model, Draw DIAGRAM). Electrons have to be excited into energy levels, and this leads to atomic spectra. (DRAW atomic spectra).

10.4 Tutorial quiz

Atoms emit and abosrb energy in ——— amounts (quantized)?

11 Week 11 - Double slit experiment and uncertainty principle

11.1 Review of last week

- We wrapped up GR with a discussion of black holes.
- The photoelectric effect. The fact that electrons are only free'd when the photon has a specific wavelength and not with the number of photons.
- Blackbody emits all the radiation it absorbs.

11.2 Atomic structure

- The atom consists of a nucleus with protons and neutrons, and electrons orbiting the nucleus.
- The radial distance to an electron is not a continuous variable. I.e the electron can only sit at fixed radial distances from the nucleus. This corresponds to fixed energy levels (potential energy depends on the radius).
- When an electron goes from one energy level to another it makes a quantum jump in energy and this energy is emitted with a photon with energy $\Delta E = h\omega$.
- This is how spectroscopy works and atomic spectra are calculated. This is one of the first predictions of QM that was tested. The calculation and observation of the hydrogen energy levels.
- Now, one has to remember QM can only predict probabilities of things. So the structure of the atom is rather fuzzy. There is a probability distribution that tells us in what region of space the electrons sit in the atom. This is very different to classical physics. It also means, there is a nonzero probability of an electron existing anywhere in the universe!

11.3 double-slit experiment

- The double slit experiment we talked about in the class about waves.
- Remarkably the same thing is observed with electrons. Even when electrons are released one by one.
- This also leads us to postulate that electrons can have wavelike and particle like behaviour. $p = h/\lambda$. This behaviour is always true (no matter what the object is).

11.4 Uncertainty principle

All these experimental pieces of evidence lead to the amazing fact that you cannot know the position and momentum of a particle exactly. Even in principle.

There is a simple reason for this: consider a the way you make a measurement. You fire a photon to an object and wait till it bounces back. But a photon is a like a particle that has a momentum $p = h/\lambda$. When it hits the object that you want see, it exchanges some momentum with it and so disturbs the objects. So there is no way to known the position or momentum of the particle exactly.

This has some very profound consequences. Indeed, mathematically the state of system in QM is described by a wavefunction. The wavefunction gives probabilities for things, like the position and momentum of the particle. And this can have a nonzero probability in very strange situations - for example the probability of a particle existing at the edge of the universe is nonzero.