G.1 Frames of reference

G.1.1 Recognise, describe and construct examples of inertial frames of reference

Inertial frame of reference- a frame of reference in which the law of inertia, Newton's first law, does hold, i.e. where there is no acceleration, in direction or speed

G.1.2 Use the Galilean transformation equations to calculate relative velocities for objects moving at non-relativistic speeds

$$u_x = \frac{\Delta x}{\Delta t} = \frac{\Delta x'}{\Delta t'} + v = u'_x + v = u'_x + v$$

G.1.3 Recognise, construct and interpret examples of accelerated frames of reference

Accelerated frame of reference-a frame of reference in which there is an acceleration and Newton's first and second laws do not hold.

G.2 Historical context

G.2.1 Qualitatively explain Maxwell's prediction of the existence of electromagnetic waves which travel at the speed of light

- Maxwell knew a changing magnetic field produced a changing electric field. He hypothesised that a changing electric field would thus produce a changing magnetic field.
- Oscillating charges undergo acceleration which results in electromagnetic disturbances which travel through space as waves, i.e. light waves are electromagnetic in nature

G.2.2 Describe the Michelson-Morley experiment, and explain its objective, results and the significance of its outcome

- Designed to measure the speed of the ether, the medium in which light was assumed to travel with respect to the Earth, hoping to establish am absolute reference frame, one that can be considered at rest.
- Interferometer used to measure the difference in the speed of light in different directions to the accuracy that would be needed, looking at different interference patterns by splitting up light using a half-silvered mirror, making them travel perpendicularly for equal lengths when they are reflected back, which are then superimposed creating an interference pattern. It was assumed that the either *ether wind*, or that the Earth would move in respect to the stationary ether and this would cause one of the beams of light to travel back faster and cause a different interference pattern.
- There **was no significant fringe shift** in any direction, at any time of the year. This 'null' result was explained by Fitzgerald and Lorentz when they proposed length contraction by the factor $\sqrt{1-v^2/c^2}$ in the direction of motion through the ether, this was replaced by Einstein's Special Theory of Relativity. It was found that the speed of light is the same in all inertial frames of reference

G.3 Postulates and fundamental concepts of special relativity

G.3.1 State the two postulates of the special theory of relativity

- **The relativity principle**- The laws of physics have the same form in all inertial reference frames

- **Constancy of the speed of light**- light propagates through empty space with a definite speed *c* independent of the speed of the source or the observer

G.3.2 State that special relativity links three dimensions of space and one dimension of time to describe a four-dimensional space-time

- Special relativity links three dimensions of space and one-dimension of time to describe a four-dimensional space-time!!! Two observers will describe the same event with different space-time coordinates

G.3.3 Discuss and apply the concept of simultaneity

- Under the theory of relativity, we cannot regard time as an absolute quantity, the time interval between two events and the determination of whether or not two events are simultaneous depends on the observer's frame of reference. Two events which are simultaneous in one frame of reference will not be simultaneous in another frame which is moving with respect to the first.
- Simultaneity is dependent on the state of motion of the observer, both observers will be correct because there is no preferred frame of reference

G.3.4 Explain how the observation of an event depends on the observer's frame of reference and on the observer's relative motion with respect to the frame of reference in which the event has occurred

- If two observers are moving relative to each other, one may see two events to be simultaneous, however, the other will not. Simultaneity is a relative concept

G.4 Development and experimental support of basic effects of special relativity

G.4.1 Define 'proper time' and solve problems using the time dilation equation

- **Proper time**- a time interval measured in a frame of reference between two events which occur at the same point in space
- **Time dilation**- $\Delta t = \dfrac{\Delta t_o}{\sqrt{1/v^2/c^2}}$ where _t_o is proper time, since the events of the light pulse leaving the source and returning to the time occur at the same point in space
- Clocks moving relative to an observer are measured by that observer to run more slowly compared to clocks at rest

G.4.2 Explain the twin 'paradox'

- If a twin goes away and travels at relativistic speeds, in comparison to the twin at rest, his time will move more slowly and thus, the twin who goes away should age slower. However, to the twin who goes away, the other twin is travelling at a relativistic speed in the other direction and thus, time should move more slowly for this twin. So if they met up again, after 100 years, what would happen? PARADOX!
- The special theory of relativity deals only with inertial frames of reference, the astronaut twin would have undergone **huge accelerations**, thus his frame is not inertial

G.4.3 Define 'proper length' and solve problems using the length contraction equation

- **Proper length**-The length of an object, or the distance between two points whose positions are measured at the same time as measured by an observer who as at rest with respect to it.

- **Length Contraction**- $L = L_o\sqrt{1 - v^2/c^2}$, the length of an object is measured to be shorter when it is moving relative to the observer than when it is at rest

G.4.4 Discuss muon decay as experimental evidence for time dilation and length contraction

- Muons, whose mean lifetime is 2.2 μs at rest. Careful experiments showed that when a muon travels at high speeds, its lifetime from the Earth's point of reference is much longer than it is at rest. The length is also contracted as the muon is moving at relativistic speeds and to the muon, it travels a much shorter distance in a given time

G.4.5 Define 'rest mass' and use the mass increase equation to solve problems

- **Rest mass**- the mass of an object as measured in a reference frame in which it at rest
- **Mass increase**- $m = \frac{m_o}{\sqrt{1 - v^2/c^2}}$

G.4.6 Qualitatively compare the addition of velocities at normal and relativistic speeds

- Galilean relativity of objects implies objects can travel faster than the speed of light
- At normal speeds, you just add the velocities, at relativistic speeds the correct formula is

$$u = \frac{v + u'}{1 + vu'/c^2}$$, if 'u' is in the same direction as 'v'

G.4.7 Apply Einstein's mass-energy equivalence relation

- If we accelerate an object, not only does its speed increase, but also its mass, thus the work we do increases its mass, thus mass is a form of energy
- K.E = $mc^2 – m_oc^2$, where m_oc^2 is the rest energy
- Thus $E = mc^2$ or $E = m_oc^2 + KE$
- Also _E = (_m)(c^2)

G.4.8 Construct and interpret space-time diagrams

- All three-dimensions of space are squished into one on the horizontal axis, with the vertical axis being that of time
- Vertical lines represents a stationary object, horizontal lines represent all points at a given instant in time

G.7.1 Derive the time dilation equation

$$\Delta t_o = \frac{2D}{c}$$

$$c = \frac{2\sqrt{D^2 + L^2}}{\Delta t}$$

$$c = \frac{2\sqrt{D^2 + L^2(\Delta t)^2/4}}{\Delta t}$$

$$c^2 = \frac{4D^2}{(\Delta t)^2} + v^2$$

$$\Delta t = \frac{2D}{c\sqrt{1 - v^2/c^2}}$$

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

G.7.2 Derive the length contraction equation

$$L = v\Delta t_0$$
$$\text{but}\,\Delta t_0 = \Delta t\sqrt{1 - v^2/c^2}$$
$$\text{and}\,\Delta t = L_0/v$$
$$\therefore L = v\Delta t\sqrt{1 - v^2/c^2}$$
$$L = L_0\sqrt{1 - v^2/c^2}$$

G.7.3 Qualitatively solve problems involving the relativistic addition of velocities

$$u = \frac{v + u'}{1 + vu'/c^2}$$, if 'u' is in the same direction as 'v'

G.7.4 Distinguish between rest energy and total energy, and deduce an expression for relativistic kinetic energy

- **Rest energy**- m_0c^2 the amount of energy that an object at rest has
- **Total energy**- $mc^2 = KE + m_0c^2$, assuming no potential energy
- **Relativistic Kinetic Energy**- $KE = m_0c^2\left(\frac{1}{\sqrt{1 - v^2/c^2}} - 1\right)$

G.7.5 Solve problems relating momentum to the total energy

$$p = mv = \frac{m_0 v}{\sqrt{1 - v^2/c^2}}$$

since $E^2 = m^2c^2$

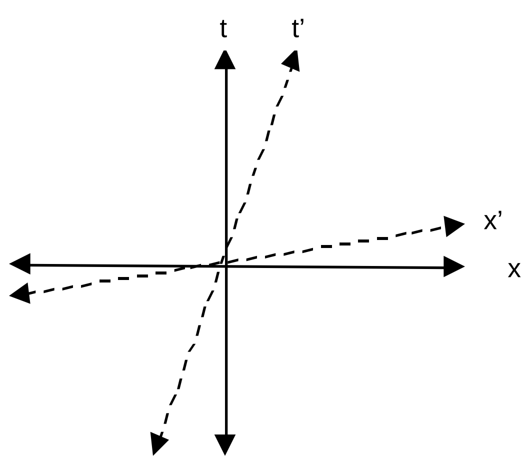
$$E^2 = p^2c^2 + m_0^2c^4$$

G.7.6 Apply Einstein's mass-energy equivalence equation to problems involving objects moving at relativistic speeds

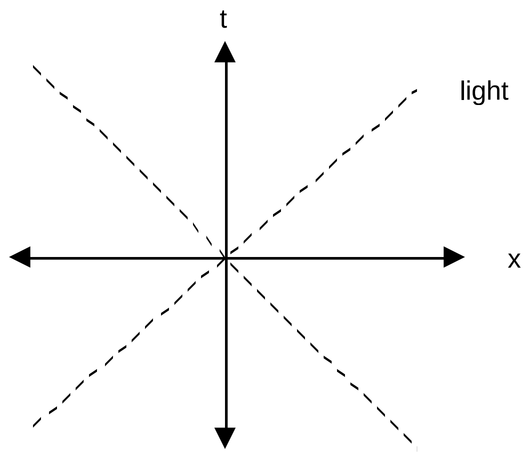
$$KE = mc^2 - m_0c^2$$

G.7.7 Solve quantitative problems involving space-time problems

- At a certain slope, an object travels at the speed of light, i.e. greater slopes are not possible. The slower the speed, the closer the line is to the 't' axis
- For a moving observer, the axes change, with x' becoming a line of constant time, passing through O and t' becoming a line of constant position. The grid below is the product of the assumption that the speed of light is constant for all observers



- Say, for the moving observer, x' and t' axes, a line of constant time will be parallel to the x' axis, while a line of constant position will be parallel to the t' axis.
- **Light cones**- a light cone divides a space-time diagram into two major sections, the area inside and the area outside the cone, with the slopes representing the speed of light in the forward and backward directions. It is impossible for anything to travel faster than the speed of light, thus an event at O can only be observed at a certain time in a certain position



G.5 Postulates and fundamental concepts of general relativity

G.5.1 State Einstein's principle of equivalence

- Gravity and accelerated motion are fundamentally equivalent, 'No observer can determine by experiment whether he or she is accelerating or is in a gravitational field'
- According to the principle of equivalence, an upwardly accelerating elevator is the same as a gravitational field directed downwards, thus, light will be bent by a gravitational field

G.5.2 Describe Einstein's explanation of gravity

- Einstein held that space-time is curved, explaining gravity as the effect we detect when we observe objects moving in curved space. In four-dimensional space-time, masses warp the space around them and objects change their path because of this warped space

G.5.3 Compare gravitational mass and inertial mass

- **Inertial mass**- the mass which defines the acceleration for a given force (F = m**a**), i.e. a resistance to a force
- **Gravitational mass**- the mass which defines the force acting in a given gravitational field, i.e. weight
- It was found that these two types of mass are fundamentally equivalent

G.6 Development and experimental support of basic effects of general relativity

G.6.1 Explain the deflection of starlight as a prediction of the general theory of relativity and describe an example of experimental evidence of this effect

- **The apparent bending of light as it passes near a massive body**- conclusively observed during the solar eclipse of 1919, when the Sun was silhouetted against the Hyades star cluster for which the positions were well known. Sir Arthur Eddington measured the stars in Africa and compared these measurements to those made in Brazil. The results showed that the light was bent as it grazed the Sun by the exact amount of Einstein's predictions. The apparent displacement of light reslts from the warping of space in the vicinity of the massive object through which light travels, the light doesn't change course, it merely follows the curvature of space, this displacement is referred to as **gravitational lensing**.
- A more accurate means is to observe how the sun bends radiation from radio sources such as quasars which are 8 billion light years away by a galaxy only 400 billion light years away
- Mercury's slight shift in its elliptical path were explained by Einstein's theory that gravity bends space-time

G.6.2 define the term 'gravitational redshift', understand that it is a prediction of the general theory of relativity, and describe an example of experimental evidence

- **Gravitational redshift**- light travelling through a gravitational field will shift towards the redder regions of the spectrum, the light leaving a mass depends on the magnitude of the mass. **Example**- Pound-Rebka experiment of 1960 measured the frequency shift of gamma ray photons

G.6.3 Give a qualitative description of the formation and properties of a black hole

- **Black hole**- when a star collapses, it gets more dense, Einstein predicted that a strong gravitational field will redshift radiation and it will be bent by a strong gravitational field. When a star collapses, its surface gravity increases, radiation from the star is increasingly redshifted and radiation leaving the star at an angle that is not perpendicular to the surface will be bent more and more. Eventually, radiation from the star can no longer escape into space; the escape velocity is greater than that of light. Radiation from other sources that hit the surface will not be reflected, but totally absorbed.

Schwarchild radius, $R = \frac{2GM}{c^2}$

G.8.1 Qualitatively apply the equation for gravitational redshifts to determine the frequencies of radiation or the height above the surface

- For small differences in height, _h, between clocks, the shift in frequency _f is given by:

$$\frac{\Delta f}{f} = \frac{g\Delta h}{c^2}$$

G.8.2 Explain that the general theory of relativity predicts the existence of gravitational waves (or gravitational radiation) and describe experimental tests designed to test this theory

- Just as an electric charge that is accelerated emits electromagnetic waves, a mass can also lose energy emitting gravitational waves if it vibrates, a spherical mass emits gravity waves if it vibrates in a non-spherically symmetrical way.

- These waves travel at the speed of light and can propagate through vacuum, they also have a particle side, which is a massless particle called the **graviton**. This wave disturbs space and time.
- In 1974, a binary pulsar of roughly the same mass was used to detect a decrease in the orbital period of the binary pulsar. It was found the stars are losing energy, getting closer to each other and moving faster, with a decrease in the orbital period of 75 ms per year, this is the **only** evidence.