Physics **Core Topic 9.2**

Space

Summary of Contextual Outline

- Scientists draw on other areas of science to develop viable spacecraft
- Launch, re-entry and landing are dangerous
- Huge forces area required to enable a spacecraft to escape the Earth's gravitational field or maintain an orbit
- Rapid advances in technology allows for the exploration of the Universe
- Space research has impacted on society through development of related technologies

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1. The Earth has a gravitational field that exerts a force on objects both on it and around it

Students learn to:

- Define weight as the force on an object due to a gravitational field

Weight is defined as the force on a mass due to the gravitational field of a large celestial body, such as the Earth. It is a force and it is measured in Newtons. We can derive $F = mg$ from Newton's Second Law of Motion, $F = ma$.

- Explain that a change in gravitational potential energy is related to work done

Gravitational potential energy is the energy that a mass possess due to its position within a gravitational field. Gravitation is a force of attraction, and if an object in the Earth's gravitational field is moved further away from the centre of the Earth, work must be done on the object. That is, the object gains gravitational potential energy because it moves against the field. Conversely, if an object moves closer to the centre of the Earth, some of its gravitational

Gravitational potential energy is the energy of a mass due to its position within a gravitational field. Because gravitation is a force of attraction, if an object is moved from a point in the Earth's gravitational field to a point further away from the centre of the Earth, work must be done on the object; that is, the object moves against the field, and so it gains gravitational potential energy. Conversely, if an object moves closer to the centre of the Earth, some of its gravitational potential energy is changed into kinetic energy. In such a case, work is done by the object instead of on the object.

- Define gravitational potential energy as the work done to move an object from a very large distance away to a point in a gravitational field:

$$E_p = -G\frac{m_1 m_2}{r}$$

Gravitational potential energy is the energy of a mass due to its position within a gravitational field. Due to the inverse square relationship in the Law of Universal Gravitation, the force of attraction between a planet and an object will become zero only at an infinite distance away from the planet. We therefore define infinity (or some point a very large distance away) as the level of potential energy. Because work is done on an object (that is, energy is given to the object) when it is moved to infinity, all objects within a gravitational field have a negative gravitational potential energy.

Students:

- Perform an investigation and gather information to determine a value for acceleration due to gravity using pendulum motion or computer-assisted technology and identify reason for possible variations from the value 9.8 ms^{-1}.

Pendulum motion:

When a pendulum swings with a small angle, the mass on the end undergoes a motion called simple harmonic motion. The period of the pendulum is given by $T = 2\pi\sqrt{\frac{l}{g}}$.

- Measure the length of the pendulum from the knot at it top to the base of the mass carrier
- 30° maximum deviation from vertical
- Use stopwatch to time 10 complete back-and-forth swings
- Start and stop stopwatch at extreme instead of somewhere in the middle
- Adjust length of string
- Graph of results: Plot T^2 on the vertical axis and length l on the horizontal axis; gradient can be used to find the value of g

Variations in the value of g:

- The Earth's crust or lithosphere shows variations in thickness and structure due to tectonic plate boundaries and dense mineral deposits.
- The Earth is not a perfect sphere, but is flattened at the poles. This means that the value of g will be greater at the poles, since they are closer to the centre of the Earth.
- The spin of the Earth creates a centrifuge effect that reduces the effective value of g. the effect is greatest at the Equator and there is no effect at the poles.
- Variation with altitude: the further away from the centre of the Earth, the lower the value of g, as given by: $g = G\frac{m_E}{(r_E + \text{altitude})^2}$

- Gather secondary information to predict the value of acceleration due to gravity on other planets

  The formula used here is $g = G\frac{m_{planet}}{{r_{planet}}^2}$

- Analyse information using the expression $F = mg$ to determine the weight force for a body on Earth and for the same body on other planets

2. Many factors have to be taken into account to achieve a successful rocket launch, maintain a stable orbit and return to Earth

Students learn to:

- Describe the trajectory of an object undergoing projectile motion within the Earth's gravitational field in terms of horizontal and vertical components

A projectile is any object that is projected into the air and then left to complete its flight under the influence of only one force, the force of gravity. The trajectory is the path that is takes, and in the absence of air resistance, the path of the flight of a projectile will trace out the shape of a parabola. In analysing this motion, we observe that the motion of a projectile can be regarded as two separate and independent motions superimposed upon each other. The first is a vertical motion, which is subject to acceleration due to gravity, and the second is a horizontal motion, which experiences no acceleration. Because the two motions are perpendicular, and therefore independent, we can treat them separately and analyse them separately.

- Describe Galileo's analysis of projectile motion

Galileo postulated that all masses, whether large or small, fall at the same rate. Projectiles are projected into the air and then left to complete their flight in freefall. Throughout the flight, the projectile is subject only to the acceleration due to gravity, g. This rate of acceleration applies to all objects, large or small. All objects are accelerated towards the Earth at the same rate. Galileo realised that the natural shape of projectile motion was that of the parabola.

Galileo conducted experiments to try to prove this. However, air resistance interfered with his results. He eventually overcame this by rolling balls down highly polished inclines, which reduces the effective acceleration; this lower rate of acceleration was less affected by air resistance and was easier to measure.

- Explain the concept of escape velocity in terms of the a) gravitational constant b) mass and radius of the planet

By considering the kinetic and gravitational potential energy of a projectile, it can be shown mathematically that the escape velocity of a planet depends only upon the universal gravitational constant *G*, the mass and radius of the planet. To escape the gravitational field of the planet, the projectile must have positive energy, which means that the magnitude of the projectile's kinetic energy must be greater than the magnitude of its gravitational potential energy. Mathematically, $\frac{1}{2}m_o v^2 > -G\frac{m_o m_e}{r}$, where m_0 and m_e are the masses of the object and Earth respectively. This reduces to Escape velocity = $\sqrt{\frac{2Gm_e}{r_e}}$, which is determined by only the mass and radius of the planet.

- Outline Newton's concept of escape velocity

If we throw an object up, it will rise to a certain height before falling back to Earth. If thrown faster, it will rise higher. The reasoning behind escape velocity is that if the object is thrown fast enough, it should rise up and continue to rise, slowing down but never returning to Earth. It will come to rest only when it has completely escaped the Earth's gravitational field (at infinity).

- Identify why the term 'g forces' is used to explain the forces acting on an astronaut during launch

The term '*g* force' is used to express a person's apparent weight as a multiple of his/her normal true weight, the weight when standing on the surface of the Earth. The sensation of weight a person feels is the apparent weight, which is equal to the sum of the forces resisting the true weight, including the normal reaction force from the floor, and the trust of a rocket engine. Thus, during launch, the floor meets the astronaut's downward weight force with an upward reaction force, and in addition, the floor exerts an upward accelerating force. The astronaut's apparent weight is greater than his/her normal weight, and this is expressed as a multiple of *g*.

- Discuss the effect of the Earth's orbital motion and its rotational motion on the launch of a rocket

By addition of vectors, a moving platform offers a boost to the velocity of a projectile launched from it, if launched in the direction of motion of the platform. Because the Earth is revolving around the Sun, and is rotates around its axis once per day, the Earth is itself a moving platform with two different motions to be exploited in a rocket launch to gain a boost in velocity.

To achieve the velocity needed for a stable orbit, the rocket can be launched in the direction of the Earth's rotation, that is, towards the east. In this way, the rotational velocity of the launch site relative to the Sun will add to the orbital velocity of the rocket relative to the Earth, to produce a higher orbital velocity relative to the Sun.

In the same way, engineers planning a rocket mission heading further into space can exploit the Earth's revolution around the Sun by planning the launch for a time of year when the direction of the Earth's orbital velocity corresponds to the desired heading. The rocket proceeds in its orbit until the direction of its orbital velocity corresponds to that of the Earth.

In this way, the Earth's orbital velocity relative to the Sun adds to the rocket's orbital velocity relative to the Earth, to produce a higher velocity achieved by the rocket relative to the Sun.

- Analyse the changing acceleration of a rocket during launch in terms of the a) Law of Conservation of Momentum a) forces experienced by astronauts

The Law of Conservation of Momentum states that during any interaction in a closed system the total momentum of the system remains unchanged, which means that during a lunch, the magnitude of the momentum of the gases shooting out the back must be equal to the momentum of the rocket itself.

$$\text{Total change in momentum} = 0$$
$$\therefore -\Delta p_{gases} = \Delta p_{rocket}$$
$$-\Delta(mv)_{gases} = \Delta(mv)_{rocket}$$

Hence, the mass of the gases during any given second is less than the mass of the rocket, which means that the velocity gained by the rocket is less than that of the gases. However, as the mass of the rocket decreases as fuel is burnt, change in velocity Δv will increase. Rockets that use liquid-fuel engines can be throttled, which gives the rocket the ability to vary the launch thrust between 50% and 100%.

Prior to lift-off, a rocket has zero acceleration, because of the balance that exists between the weight force and the reaction force plus the thrust. The astronaut thus experiences a one g load. This initial condition will not change until the building thrust exceeds the weight of the rocket, and which point the rocket will lift off.

Since thrust now exceeds weight, there is net force acting upwards on the rocket, and so it accelerates upwards. The g force experienced by the astronauts will have a value slightly greater than one. However, as fuel is burnt, the acceleration increases, and so the astronauts will experience higher g forces.

Multi-stage rockets drop the spent stage away, and experience zero g conditions momentarily, acting as a projectile. The next stage fires and the rocket develops the necessary thrust to exceed the effective weight at its altitude, and starts to accelerate again, with the g forces experienced gradually building to a maximum value. This process is repeated for each stage of the rocket. In order to avoid extreme g forces, there is a sequential shutdown of the multiple rockets of each stage.

- Compare qualitatively low Earth and geo-stationary orbits

Low Earth orbit	Geostationary orbit
▪ A low Earth orbit is generally an orbit higher than 250 km, in order to avoid atmospheric drag, and lower than 1000 km, which is the altitude at which the Van Allen radiation belts start to appear	▪ The altitude is about 35 800 km (radius of orbit around 42 000 km, then subtracting the radius of the Earth), determined by using Kepler's Law of Periods
▪ At 250 km, an orbiting spacecraft takes just 90 minutes to complete an orbit	▪ Period of the orbit matches that of the Earth; if over the equator, it will remain stationary over a fixed point
▪ Space shuttle utilises a low Earth orbit between 250 km and 400 km	▪ Particularly useful for communications satellites because receiving dishes only need to point to a fixed spot in the sky; also at upper limits of Van Allen radiation belts and near the edge of the magnetosphere, making them useful for scientific purposes

- Define the term orbital velocity and the quantitative and qualitative relationship between orbital velocity, the gravitational constant, mass of the satellite and the radius of the orbit using Kepler's Law of Periods

Orbital velocity is the rate of change of the direction of a point moving with circular motion as measured from a point at rest; the magnitude of orbital velocity for a point moving with circular motion is constant.

Kepler's third law (the Law of Periods) $\frac{r^3}{T^2} = \frac{Gm_E}{4\pi^2}$ = a fixed value

When the period is known, the orbital velocity can be found by $v = \frac{2\pi r}{T}$

The mass of the satellite plays no part in determining the orbital velocity at a particular distance away from the centre of the orbit.

$\frac{r^3}{T^2}$ is a constant value for all bodies orbiting the same object.

- Account for the orbital decay of satellites in low Earth orbit

All satellites in low Earth orbit are subject to some degree of atmospheric drag (friction) that will eventually decay their orbit and limit their lifetimes. Over a period of time, the satellite will slow down. As it slows down, its kinetic energy decreases. Because a lower orbit corresponds to a lower energy, the satellite must lost altitude if it slows down. This result can also be derived using Kepler's Third Law; if the orbital velocity, and hence the period, decreases, radius must decrease since $\frac{r^3}{T^2}$ must remain a constant. As it descends, it encounters higher density air and higher drag, speeding up the process.

The amount of atmospheric drag experienced by a satellite depends on the size of the satellite and the density of the air along the orbit. The air density is affected by variables such as time of day, season, latitude and longitude. An increase in solar wind heats up the outer atmosphere, increasing its density at a particular height.

- Discuss issues associated with safe re-entry into the Earth's atmosphere and landing on the Earth's surface

As the spacecraft re-enters, it experiences friction with the molecules of the atmosphere and causes it to decelerate. The spacecraft's velocity and orbit means that it has considerable kinetic energy and gravitational potential energy, which is lost during re-entry. This energy is converted into heat, and the heat can cause the spacecraft to reach extreme temperatures, which can vaporise the spacecraft.

The best shape for re-entry is a blunt one, because it will produce a shock wave in front of itself, and that will carry the energy away. For example, the space shuttle keeps its nose up while re-entering, and it presents its flat underbelly to the atmosphere to create the shock wave.

However, the blunt design would still need to cope with high temperature. The technique of ablation involves covering the nosecone with a ceramic material, which is vaporised or 'ablated' during re-entry. The vaporisation of the surface dissipates the heat and carries it away. The space shuttle uses insulating tiles that are 90% air, giving them excellent thermal insulation properties.

There is also a need to consider the survival of any living occupants. Greater angles of re-entry mean greater rates of deceleration, which would lead to greater g forces experienced by the astronauts. The maximum safe load on an astronaut is about 8 g, but there are ways to increase a human's tolerance of g forces. The astronaut should lie down, because transversal applications of g forces are easier to handle as blood as not forced away from the brain.

Tolerance can be increased by supporting the body in as many places as possible, such as by using a contoured couch.

- Identify that there is an optimum angle for safe re-entry for a manned spacecraft into the Earth's atmosphere and the consequence of failing to achieve this angle

There is a window of approximately 2 degrees for re-entry. If the angle of re-entry is too shallow, the spacecraft may skip off the atmosphere, and if the angle of re-entry is too steep, the spacecraft will burn up due to the heat of re-entry.

Students:

- Solve problems and analyse information to calculate the actual velocity of a projectile from its horizontal and vertical components using $v_x^2 = u_x^2$, $v = u + at$, $v_y^2 = u_y^2 + 2a_y \Delta y$, $\Delta x = u_x t$, $\Delta y = u_y t + \frac{1}{2} a_y t^2$

- Perform a first-hand investigation, gather information and analyse data to calculate initial and final velocity, maximum height reached, range and time of flight of a projectile for a range of situations by using simulations, data loggers and computer analysis

- Identify data sources, gather, analyse and present information on the contribution of the following to the development of space exploration: Tsiolkovsky, Oberth, Goddard, Esnault-Pelterie, O'Neill or von Braun
    - Considered the theoretical father of rocketry, he theorised many aspects of space travel and rocket propulsion before others, and played an important role in the development of Russian space programs
    - Influenced by science fiction, he began to introduce real technical problems into his writings, and his dream was for humanity to become a space civilisation
    - He demonstrated the reaction principle by experimenting with a cask filled with compressed gas; he discovered that the movement of the cask could be regulated by alternating the pressure of the gas released from it
    - He outlined how a reaction thrust motor could demonstrate Newton's Third Law to allow humans to escape the bounds of Earth
    - His drafted design for the first rocket involved an explosive mixture of liquid oxygen and liquid hydrogen, which produces condensed and heated gases; these gases are cooled and rarefied with the resulting exhaust providing the thrust
    - He also speculated on a multi-stage approach to spaceflight; as each individual stage consumed its fuel, it would be discarded to keep the overall weight to a minimum; he recognised that it would require a tremendous amount of fuel for the rocket to reach escape velocity
    - He wrote over 500 scientific papers, and although he did not create any rockets himself, his fundamental principles remain basic to contemporary astronautics
- Solve problems and analyse information to calculate centripetal force acting on a satellite undergoing uniform circulate motion about the Earth using: $F = \frac{mv^2}{r}$

- Solve problems and analyse information using: $\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$

3. The Solar System is held together by gravity

Students learn to:

- Describe a gravitational field in the region surrounding a massive object in terms of its effects on other masses in it

A gravitational field is a field in which any mass will experience a gravitational force. Since the force of gravity acts on masses surrounding the Earth, or any massive object, a gravitational field exists around the Earth or the massive object, with the gravitational field taking on a radial pattern with the field lines pointing towards the massive object's centre. This is because this is the direction of the force that would be experienced by a mass within the field, that is, towards the large object's centre. Closer to Earth or the massive object, the field lines are closer together, indicating that the field, and its force, are stronger in this region.

On a small scale, such as the interior of a room, the field lines, or lines of force, appear parallel and point down since that is the direction of the force that would be experienced by a mass placed within the field.

- Define Newton's Law of Universal Gravitation

$$F = G\frac{m_1 m_2}{d^2}$$

Newton's Law of Universal Gravitation states that the force of attraction between two masses is proportional to the product of the masses and inversely proportional to the square of the distance between their centres. This force is exerted equally on both masses.

- Discuss the importance of Newton's Law of Universal Gravitation in understanding and calculating the motion of satellites

If a satellite undergoes uniform circular motion, there must be a centripetal force acting to maintain circular motion, which is directed towards the centre of the circle. This is because an object will continue in uniform motion in a straight line unless acted upon by a force, according to Newton's First Law of Motion. In the case of a satellite, it is the gravitational attraction between the Earth, or another massive object, and the satellite that acts as the centripetal force.

By equating the mathematical expressions for Newton's Law of Universal Gravitation and centripetal force:

$G\frac{m_E m_S}{r^2} = \frac{m_S v^2}{r}$, where m_E is the mass of the Earth and m_S is the mass of the satellite

This reduces to $v = \sqrt{\frac{Gm_E}{r}}$, and from this, we can see that the orbital velocity required for a particular orbit depends only on the mass of the Earth (or the other body being orbited), the radius of the orbit. Since the mass of the Earth is a constant, this means radius (or altitude since the radius of the Earth is also a constant) is the only variable that determines the required velocity. The greater the radius of the orbit, the lower the orbital velocity required.

- Identify that a slingshot effect can be provided by planets for space probes

The slingshot effect, or planetary swing-by, is a manoeuvre used with space probes to pick up speed and proceed on to another target. Even though there is no contact, the interaction behaves as a collision, because the spacecraft is captured by the planet's gravitational field for a period of time; however, because the bodies do not touch in any way, there are no energy losses and hence the collision is elastic.

If we consider the velocity of the spacecraft relative to a planet, then it is possible to assume that the planet is standing still. When a small object collides with elastically with a very large, massive object, the small object will rebound without loss of speed, like a ball bouncing off a wall. However, the planet is moving relative to the Sun, and by vector addition, the speed of the spacecraft relative to the Sun is its original speed plus the speed of the planet, if we assume that the interaction happens one-dimensionally. Some of the planet's momentum is transferred to the spacecraft, which results in the spacecraft having a higher velocity.

The slingshot effect can also be used to change the direction of a spacecraft's motion.

Students:

- Present information and use available evidence to discuss the factors affecting the strength of the gravitational force
  - Using $F = G\frac{m_1 m_2}{d^2}$, the strength of the gravitational force is proportional to the product of the two masses, and inversely proportional to the square of the distance between their centres
  - The force acts equally on both masses
  - The value of g on Earth varies according to geographical location and altitude

- Solve problems and analyse information using: $F = G\frac{m_1 m_2}{d^2}$

4. Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

Students learn to:

- Outline the features of the aether model for the transmission of light

Nineteenth-century physicists, having concluded that light moves as a waveform, observed that many other wave motions required a medium through which to travel. Consequently, the 'luminiferous aether' was the proposed medium for light and other electromagnetic waves, before it was realised that these waveforms do not need a medium in order to travel. The aether:

  - Filled all of space, had low density and was perfectly transparent
  - Permeated all matter and yet was completely permeable to material objects
  - Had great elasticity to support and propagate the light waves

- Describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the aether

If the aether did exist, the Earth should be moving through the aether. From our point of view, we should experience a flow of aether past us called the 'aether wind'. However, the aether was thought to be extremely tenuous, so any aether wind would be hard to detect. There were many experiments designed and performed to detect it, but they all failed. The assumption was that the detection mechanisms were simply not sensitive enough.

Michelson and Morley's experiment was exceedingly sensitive. They used the effect of interference of light waves in order to measure the relative velocity of the Earth through the aether. A light wave from a source is split into two perpendicular beams by the half-silvered mirror. One ray would travel into the supposed aether and the other across it. Mirrors reflect the two rays back, and the rays are recombined at the interferometer, where a series of dark and light bands can be seen. If the aether wind exists, the rays would travel at different velocities; when the apparatus is rotated, the interference pattern should be seen to shift, and the relative velocity of the aether wind can be determined by using this shift.

However, the result of the experiment was null, that is, no such shift was observed. The experiment was repeated many times by Michelson and Morley, at different times of the day and year. Further, the Michelson-Morley experiment has been repeated many times since then by different groups with more sensitive equipment. No evidence of the aether has ever been found, and suggestions to explain the null results of the experiment have not survived close scrutiny.

- Discuss the role of the Michelson-Morley experiments in making determinations about competing theories

The results of the Michelson-Morley experiments were null, meaning that no aether was detected. However, the scientific community was not quick to abandon the aether model, and adapted the theory to keep it alive. One suggestion was that a large object such as a planet could drag the aether along with it. Another was that objects contract in the direction of the aether wind. However, none of these modifications withstood close scrutiny.

Galileo posed a simple idea, now called the 'principle of relativity', which states that all steady motion is relative and cannot be detected without reference to an outside point. Within an inertial frame of reference, you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity or standing still. However, belief in the aether posed a difficult problem for the principle of relativity, because the aether was supposed to be stationary in space, and light was supposed to have a fixed velocity relative to the aether. Thus, an optical experiment whereby the speed of light is measured provides a way to violate the principle of relativity where no mechanical experiment could.

Einstein realised that if the principle of relativity were not to be violated, light must move at a constant speed for all observers, at $c = 3 \times 10^8 ms^{-1}$. In this way, the result of the Michelson-Morley experiments provided an observational proof of Einstein's theory, which would render the idea of the aether superfluous.

- Outline the nature of inertial frames of reference

An inertial frame of reference is a non-accelerated environment, such as one that has steady motion or no motion at all. In an inertial frame of reference, Newton's laws of motion are obeyed, and any experiment performed in an inertial frame of reference will appear the same in another inertial frame of reference. The principle of relativity states that within an inertial frame of reference, you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity or standing still.

- Discuss the principle of relativity

The principle of relativity states that all steady motion is relative and cannot be detected without reference to an outside point. The principle of relativity only applies for non-accelerated steady motion – standing still or moving with a uniform velocity. For example, when you are inside a moving vehicle, you cannot tell if you are moving at a steady velocity or standing still without looking out the window.

The principle states that within an inertial frame of reference, you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity. For example, if you held up a string with a small object tied to the end, the object would hang so that the string was vertical. However, if the vehicle in which you were travelling in accelerated, the object would swing backwards so that the string is no longer vertical. When you stop accelerating and reach a constant velocity, the string would swing back into the vertical position. When rounding corners, the string would lean one way or the other. This plumb bob acts as a simple accelerometer, but it is unable to distinguish between being motionless and steady motion.

- Describe the significance of Einstein's assumptions of the constancy of the speed of light

The speed of light through a vacuum is assumed constant relative to all observers so that the principle of relativity cannot be violated by using optical experiments. However, if observers at relative motion to each other observe the speed of light to be constant, then since speed = $\frac{\text{distance}}{\text{time}}$, then the distance and time witnessed by both observers must be different.

Because of the constancy of the speed of light, an outside observer will see that an object moving with relative velocity to the outside observer will experience time dilation, length contraction in the direction of motion, and mass dilation. In addition, because space and time become relative if the speed of light is constant, simultaneous events in one frame of reference are not necessarily observed to be simultaneous in a different frame of reference; any event has three dimensions of space and one of time.

- Identify that if c is constant then space and time become relative

By Einstein's theory, the speed of light in a vacuum has the same value *c* independent of the motion of the observer. This can only be true if an observer and another observer moving with relative motion observed different times as well as different distances in such a way that distance divided by time always equals the same value *c*. In Newtonian physics, distance and velocity can be relative terms, but time is an absolute and fundamental quantity. Einstein radically altered the assumptions of Newtonian physics so that now the speed of light is absolute, and space and time are both relative quantities that depend on the motion of the observer.

Since both space and time are no longer absolute, the theory of relativity has replaced them with the concept of a space-time continuum. Any event then has four dimensions (three space coordinates plus a time coordinate) that fully define its positive within its frame of reference.

- Discuss the concept that length standards are defined in terms of time in contrast to the original metre standard

The metre as a unit of length was first defined in 1793 when the French government decreed it to be a fraction of the length of the Earth's quadrant passing through Paris. Three platinum standards and several iron copies were made. When it was discovered that the quadrant survey was incorrect, the metre was redefined as the distance between two marks on a bar. In 1875, the Systeme Internationale (SI) of units defined the metre as the distance between two lines inscribed on a single bar of platinum-iridium alloy. Copies, or 'artefacts', were made for dissemination of this standard.

There is always a need for the accuracy of a unit of measure to keep pace with improvements in technology and science. The current definition of the metre uses the constancy of the speed of light in a vacuum and the accuracy of the definition of one second to achieve a definition that is both highly accurate and consistent with the idea of space-time. One metre is now defined as the length of the path travelled by light in a vacuum during a particular time interval.

Such a definition of a metre ensures that the metre remains the same length for all observers, irrespective of the frame of reference (the speed of light and the vibration of the Cs atom is the same for all observers).

- Explain qualitatively and quantitatively the consequence of special relativity in relation to:
  - the relativity of simultaneity

One of the consequences of special relativity is that we can no longer consider time to be an absolute quantity. The time interval between two events, even if the to events appear to be simultaneous, depends on the observer's frame of reference. Two events are said to be simultaneous if they occur at the same time. Consider the following thought experiment.

Two people are equidistant from two light flashes *x* and *y*. Person *A* is moving to the right towards *y* with a velocity *v*, while person *B* is stationary. At the instant *A* passes *B*, two light flashes occur, one at *x* (to the left), and one at *y* (to the right). The light waves will reach *B* from *x* and *y* at the same time; *B* will consider the two events to be simultaneous. However, *A* is still moving towards *y* and will observe the light flash from *y* before observing the light flash from *x*; they are not simultaneous events to *A*.

Alternatively, we can analyse the situation with a moving train. An operator of a lamp rides in the middle of a train carriage. The doors at the end of the carriage are light operated. At an instant in time when the operator is alongside an outside observer, the operator switches on the lamp, which in turn, opens the doors.

Inside the train, the operator will see the doors open simultaneously, because the light will travel the same distance at the same speed. However, to the outside observer, the train has moved while the light is travelling. The front door is further away, and the back door is closer. The light travels forwards and backwards at the same speed *c*, but the forward journey is now longer than the backward journey, so the back door is seen to open before the front door does.

If an observer sees two events to be simultaneous, then any other observer, in relative motion to the first, generally will not judge them to be simultaneous. Simultaneous events in one frame of reference are not necessarily observed to be simultaneous in a different frame of reference. Simultaneity is not an absolute concept, but is relative.

- the equivalence between mass and energy

When we accelerate an object, we must apply a force to it, that is, we do work on it:

$$W = Fs$$

However, because the speed of an object cannot exceed the speed of light, it cannot accelerate indefinitely. Usually, the work done on the object, that is, the energy being given to the object, takes the form of increased kinetic energy as the object speeds up. However, as we approach the speed of light, the energy is changed into mass, and as a consequence, the energy is no longer being used to accelerate the object.

The total energy equals the rest energy plus the kinetic energy:

$$E = E_K + mc^2$$

When an object is stationary, it has no kinetic energy, but it will have energy due to mass. This is called its rest energy, the energy equivalent of a stationary object's mass measured within the object's rest frame.

- length contraction

As a consequence of perceiving time differently (a consequence in itself of the postulates of special relativity), observers in different frames of reference also perceive length (in the direction of motion) differently. We will construct another thought experiment.

There is a 'light clock' on a train so that the light beams will run the length of the train, with the lamp and sensor located on the back wall and the mirror on the front wall. As the train passes the observer on the embankment, the light clock emits a light pulse, which travels to the front of wall and then returns to the back wall where it is picked up by the sensor, which then goes 'click'.

To an observer inside the train, the length of the light journey is simply twice that of the length of the train measured from its rest frame. However, to an observer at the side of the track, the train is moving at the same time that the light rays move. This lengthens the forward leg of the light pulse's journey and shortens the return leg. Taking into account the fact that each observer perceives time differently, we arrive at a qualitative relationship:

$$L_v = L_o\sqrt{1-\frac{v^2}{c^2}}$$

Since the term $\sqrt{1-\frac{v^2}{c^2}}$ is always less than one, the length of the train as observed by the person on the embankment is less than that observed by the person inside the train. Thus, the length of an object measured within its rest frame is called its proper length L_o, or rest length.

Measurements of this length L_v made from any other inertial reference frame in relative motion are always less.

- time dilation

Time is perceived differently by observers in relative motion to each other. A 'light clock' is arranged vertically in a speeding train, with the lamp at the ceiling and the mirror on the floor. An observer is watching from the embankment outside the train. To someone inside the train, the light beams appear to travel straight up and straight up and straight down. However, the observer on the embankment sees the light travelling along a longer journey, determined according to Pythagoras' Theorem.

The observer sees the light travel further but with the same speed, and hence time slowed down on the train. The relationship between the times observed by observers at relative motion to each other is $t_v = \dfrac{t_o}{\sqrt{1-\dfrac{v^2}{c^2}}}$, where t_o is the time as measured by the train traveller, and t_v is the time as measured by the external observer. We can see that $\sqrt{1-\dfrac{v^2}{c^2}}$ is always less than one, so t_v is always greater than t_o. Time is passing more slowly on the train as observed by the person outside the train.

Generally, let t_o be the time taken for an event to occur within its own rest frame. Measurements of this time t_v made from any other inertial reference frame in relative motion to the first, are always greater. In other words, moving clocks appear to run slow.

- mass dilation

When two particles interact with each other, the principles of conservation of momentum and conservation of energy should hold for all observers moving at arbitrary velocities with respect to the two interacting particles. By postulating momentum conservation to be true for all observers, Einstein found that the mass of an object is not measured as the same by observers with different velocities relative to the object. In other words, the mass of an object increases as its velocity increase relative to the observer:

$$m_v = \frac{m_o}{\sqrt{1-\dfrac{v^2}{c^2}}}$$

- Discuss the implications of mass increase, time dilation and length contraction for space travel

Acceleration is always the most energy costly phase of a space mission. The effect of mass accumulation (which decreases the acceleration for a given thrust) and time dilation (which means that the force will have a shorter time in which to act in), means that accelerations beyond 0.9 c will be impractical; greater and greater forces and energy input only account for marginal increases. Thus, higher speeds, which are required if humans are to reach distant locations in a reasonable timeframe, increases the energy requirements, meaning that the cost of the energy could be prohibitive.

The effect of time dilation and length contraction means that it may be possible for human astronauts to undergo exceptionally long space journeys in a reasonable amount of time, as judged by the travellers. The distance to the distant location appears to shorten, and thus the journey will appear to take less time. As well, when the astronauts return to Earth, they will have aged less time compared to the amount of time that has actually passed on Earth. This will increase the practicality of long space journeys as they may become possible to achieve within a lifetime, but the enormous speeds required for this effect to be noticeable, and hence the energy and fuel required, currently make this an impractical situation. At the speeds attained by current-day astronauts, relativistic effects due to time are negligible.

Time dilation raises the situation known as "the twin paradox". One twin stays on Earth, while the other boards a spaceship and flies off at speeds nearing *c*. This problem is often considered a paradox, because the principle of relativity demands that no inertial frame of reference be preferred over another. In other words, relativity's effects should be reversibly simply by looking at them from another viewpoint. Both siblings will see each other flying away from each other, and each can claim that the other should be younger. However, the one that boards the spaceship has accelerated and decelerated, and thus the frame of reference of the spaceship has not remained inertial. Only the Earth twin can apply time dilation in this situation because only this twin has an inertial frame of reference. Hence, the two frames of reference are not equivalent and there is no paradox because the one that stays on Earth will be younger.

Students:

- Gather and process information to interpret the results of the Michelson-Morley experiment
  - Use the example where two boats are racing each other on a river. One boat is travelling across the current, while the other travels with the current and then against the current.

- Perform an investigation to help distinguish between non-inertial and inertial frames of reference
  - Pendulum experiment: the pendulum acts as a simple accelerometer. Let a mass suspended on a line swing freely. In a non-inertial frame of reference, the mass will swing in the opposite direction to the acceleration; in an inertial frame of reference, the mass will hang vertically. This assumes that the gravitational field at that point is acting downwards.
  - Rolling balls: see whether objects within the frame of reference obey Newton's Law of Motion. Roll two identical balls across the room, the directions being perpendicular to each other. By Newton's First Law of Motion (if we ignore friction), the balls should move in straight lines across the floor, because no external force is acting on them. However, if the balls are being rolled in a non-inertial frame of reference, then they will appear to roll in the direction opposite to the direction of the acceleration. Two balls must be rolled in directions perpendicular to each other, because the acceleration may be parallel to one of the motions and be undetected.

- Analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality
  - See above notes for the 'light clocks'
  - Due to the belief in the aether model, where light has a fixed speed relative to the supposed aether, you would be able to tell whether you were moving or not by simply measuring the speed of light going one way and then the other. In other words, an optical experiment allows for relativity to be violated where no mechanical experiment could. Einstein had an ability to reduce a problem down to its simplest form and present it as a thought experiment. This was because Einstein had a strong belief in the unity of physics and the principle of relativity must not be violated.
  - The effects of relativity—relativity of simultaneity, time, length and mass—are reversible by looking at it from a different reference frame; thus, two observers moving with relative velocity may judge a situation to be different, but both are correct in their own frames of reference.

- There is evidence for the relativistic effects that follow from the assumption that the speed of light in vacuo is a constant.

▪ Analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it

- There is an abundance of mesons striking the ground. These mesons were created in the upper atmosphere by incoming cosmic rays. At the velocity of 0.996c, the mesons should take around 16 μs to travel through the atmosphere. However, when measured in a laboratory, they have an average lifetime of around 2.2 μs. This is because 2.2 μs represents their lifetime as measured in their rest frame, whereas 16 μs is a dilated lifetime due to their relativistic speed.
- Time dilation can also be verified by comparing atomic clocks that have been flown over long journeys with clocks that remained stationary for the same period. These experiments are possible now because of the extreme accuracy of modern atomic clocks. The clocks that were flown around were slow compared to those that stayed on the ground.

▪ Solve problems and analyse information using:

$$E = mc^2,\ l_v = l_o\sqrt{1-\frac{v^2}{c^2}},\ t_v = \frac{t_o}{\sqrt{1-\frac{v^2}{c^2}}},\ m_v = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}$$