TOPIC 1 Relative Motion

SQ 11.1.1 Why was relativistic mechanics developed?

Reason

At the beginning of the 20th century, new experiments and theoretical calculations revealed that classical physics based on Newton's laws could not explain phenomena involving extremely small particles or very high velocities.

SQ 11.1.2 Who introduced the special theory of relativity and when?

Answer

Albert Einstein introduced the Special Theory of Relativity in 1905.

SQ 11.1.3 What did Einstein's theory propose?

Proposal

It proposed that the laws of physics are the same for all observers, and that the speed of light is constant regardless of the observer's motion.

SQ 11.1.4 What did the special theory of relativity resolve?

Answer

It resolved the conflicts between classical mechanics and electromagnetic theory, and revolutionized our understanding of time, space and motion, forming the basis of modern physics.

SQ 11.1.5 Show with an example that direction is a relative concept.

Example

If you throw a ball to your right, for someone facing you this direction appears to be to his left. This illustrates that direction is a relative concept.

SQ 11.1.6 Show that the state of rest or motion depends on the observer.

Example

The walls of a moving train seem stationary to passengers inside the train, but appear to be moving to someone standing on the ground.

Conclusion

We cannot definitively say whether an object is absolutely at rest or in motion; all motions are relative to the observer.

SQ 11.1.7 What is observed when a ball is dropped in a stationary train?

Observation

The horizontal velocity of the ball is zero, so the horizontal distance travelled is also zero. The observations made inside and outside the train are identical, and the ball falls directly below the point from where it was dropped.

SQ 11.1.8 What is observed when a ball is dropped in a train moving with uniform velocity?

Inside Observer

Since the train and the observer inside move with the same velocity, the observer sees the ball fall directly below where it was dropped.

Outside Observer

An observer outside the train sees the ball following a projectile path.

SQ 11.1.9 What conclusion is drawn from the falling ball in a moving train?

Conclusion

Observers in different frames of reference, moving with uniform velocity relative to each other, describe the same motion differently.

TOPIC 2 Frames of Reference

SQ 11.2.1 What is meant by a frame of reference?

Definition

A frame of reference is any coordinate system relative to which measurements are taken.

SQ 11.2.2 Give examples of frames of reference.

Examples

The position of a table can be described relative to the walls of the room, making the room the frame of reference.
The laboratory is the reference frame for measurements taken there, and a moving train becomes the frame of reference for an experiment performed in it.

SQ 11.2.3 Define an inertial frame of reference.

Definition

An inertial frame of reference is a coordinate system in which the law of inertia is valid. This means a body at rest remains at rest unless acted upon by an unbalanced force that produces acceleration.

SQ 11.2.4 Why is the Earth considered an inertial frame of reference?

Reason

A body placed on the Earth remains at rest unless an unbalanced force acts upon it, indicating that the Earth can be considered an inertial frame of reference.

SQ 11.2.5 Why is a car moving with uniform velocity an inertial frame?

Reason

A body in a car moving with uniform velocity relative to the Earth also remains at rest. Thus any frame moving with uniform velocity relative to an inertial frame is also an inertial frame.

SQ 11.2.6 Define a non-inertial frame of reference.

Definition

An accelerated frame of reference is a non-inertial frame.

Example
If a car is suddenly accelerated, a body inside no longer remains at rest, so the car is not an inertial frame of reference.

SQ 11.2.7 Why is the Earth strictly a non-inertial frame, yet treated as inertial?

Reason

The Earth is rotating and revolving, making it strictly speaking a non-inertial frame. However it is often treated as an inertial frame due to its relatively small acceleration.

SQ 11.2.8 Distinguish between inertial and non-inertial frames of reference.

Inertial Frame	Non-Inertial Frame
The law of inertia is valid in it.	The law of inertia is not valid in it.
It is at rest or moves with uniform velocity.	It is an accelerated frame of reference.
The Earth is treated as an inertial frame.	A suddenly accelerated car is a non-inertial frame.

TOPIC 3 Special Theory of Relativity

SQ 11.3.1 With what does the theory of relativity deal?

Answer

The theory of relativity deals with how observers in different states of relative motion describe physical phenomena.

SQ 11.3.2 Differentiate between the special and general theories of relativity.

Special Theory	General Theory
It addresses problems involving inertial or non-accelerating frames.	It deals with problems involving frames that are accelerating relative to one another.

SQ 11.3.3 State the two postulates of the special theory of relativity.

First Postulate

The laws of physics are the same in all inertial frames, which is the principle of relativity.

Second Postulate

The speed of light in free space has the same value for all observers, regardless of the state of motion of the source or the observer.

SQ 11.3.4 What does the first postulate generalize?

Answer

It generalizes the fact that all physical laws are the same in frames of reference moving with uniform velocity relative to one another.

SQ 11.3.5 Why is there no way to detect absolute uniform motion?

Reason

If the laws of physics differed for observers in relative motion, those observers could determine which was stationary and which was moving. Since such a distinction does not exist, there is no way to detect absolute uniform motion.

SQ 11.3.6 What experimental fact does the second postulate state?

Answer

It states the experimental fact that the speed of light in free space is a universal constant, denoted as
$c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$

SQ 11.3.7 Why do space and time become relative?

Reason

Since the speed of light c is constant for all observers, space and time must themselves become relative quantities.

SQ 11.3.8 Would you see your reflection in a mirror on a train moving at the speed of light?

Answer

Yes, you will still see your reflection. This is because, according to the principle of relativity, no experiment can detect the constant motion of the train relative to the person inside it.

SQ 11.3.9 Define the relativity of simultaneity.

Definition

If two events in different locations are observed by one observer to be simultaneous, they will generally not be observed as simultaneous by another observer in a different frame of reference moving relative to the first.

SQ 11.3.10 Explain the relativity of simultaneity with the example of a train.

Example

A traveler in the middle of a train moving at half the speed of light turns on a light-operated door switch. The light reaches both doors at the same time, so the traveler sees both doors open simultaneously.

Outside Observer

An observer outside sees the back door open first, because the back door is moving towards the light waves while the front door moves away.

SQ 11.3.11 Define proper time.

Definition

Proper time t_0 is the time interval between two events measured by an observer who is stationary in the inertial frame in which the events occur.

SQ 11.3.12 Write the formula for time dilation.

Formula

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

SQ 11.3.13 Why is time said to be dilated?

Reason

Since the quantity $\sqrt{1 - \frac{v^2}{c^2}}$ is always less than one, therefore t is greater than t_0. Time has thus dilated or stretched due to the relative motion.

SQ 11.3.14 To which processes does time dilation apply?

Answer

This astonishing result applies to all timing processes, that is physical, chemical and biological. Even the aging process of the human body is slowed at relativistic speeds.

SQ 11.3.15 Give a numerical example of time dilation.

Example

If a traveler on a plane moving at $0.8c$ opens a book, the event takes one second as measured by the traveler. However, to a person standing outside the plane the same event takes 1.7 seconds.

SQ 11.3.16 What is length contraction?

Definition

If you are in motion relative to two points a fixed distance apart, the distance between them appears shorter than if you were at rest relative to them. This effect is known as length contraction.

SQ 11.3.17 In which direction does length contraction occur?

Answer

Length contraction occurs only along the direction of motion. No such contraction is observed perpendicular to the direction of motion.

SQ 11.3.18 Define proper length.

Definition

The length of an object, or the distance between two points, measured by an observer who is at rest relative to them is called the proper length ℓ_0.

SQ 11.3.19 Write the formula for length contraction.

Formula

$$\ell = \ell_0\sqrt{1-\frac{v^2}{c^2}}$$

SQ 11.3.20 Give a numerical example of length contraction.

Example

A train measured to be 100 m long at rest travels at $0.8c$. A person inside measures its length as 100 m, but a person beside the track observes it to be only 60 m long.

SQ 11.3.21 Define rest mass and write the formula for mass variation.

Rest Mass

An object whose mass is measured at rest is called its rest mass m_0.

Formula

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

SQ 11.3.22 Why does the mass of a moving object increase?

Reason

The increase in mass indicates the increase in inertia that an object has at high speeds. As v approaches c, it requires a greater force to change the object's speed.

SQ 11.3.23 Why can a material particle not move with the speed of light?

Reason

As $v \to c$, the factor $\sqrt{1-\frac{v^2}{c^2}} \to 0$, so the mass $m \to \infty$.

Result

An infinite mass would require an infinite force to accelerate it. Since infinite forces are not available, an object cannot be accelerated to the speed of light.

SQ 11.3.24 Why are Newton's laws valid in everyday situations?

Reason

In everyday life we deal with speeds extremely small compared with the speed of light. Even the Earth's orbital speed is only $30\,\mathrm{km\,s^{-1}}$, while the speed of light is $300000\,\mathrm{km\,s^{-1}}$.

SQ 11.3.25 When do relativistic effects become prominent?

Answer

When dealing with subatomic particles moving at velocities approaching the speed of light, relativistic effects become very prominent and experimental results cannot be explained without Einstein's equations.

SQ 11.3.26 A pendulum has a period of 3.0 s at rest. Find its period for an observer moving at 0.95 c.

Solution

Using

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

Calculation

$$t = \frac{3.0}{\sqrt{1-(0.95)^2}}$$

Result

$t = 9.6\,\mathrm{s}$

TOPIC 4 The Equivalence Between Mass and Energy

SQ 11.4.1 State the equivalence between mass and energy.

Statement

According to the special theory of relativity, mass and energy are distinct entities but are interconvertible.

Formula

$E = mc^2$

SQ 11.4.2 Define rest mass energy.

Definition

At rest, the energy equivalent of an object's mass m_0 is called its rest mass energy.

Formula

$E_0 = m_0c^2$

SQ 11.4.3 Write the relativistic expression for kinetic energy.

Derivation

Since mc^2 is greater than m_0c^2, the difference of energy is due to the motion of the object.

Formula

$KE = (m - m_0)c^2$

SQ 11.4.4 Write the change in mass due to a change in energy.

Formula

$\Delta m = \dfrac{\Delta E}{c^2}$

SQ 11.4.5 Why are mass changes not observed in everyday energy changes?

Reason

Because c^2 is a very large quantity, small changes in mass require very large changes in energy. In our everyday world, energy changes are too small to provide measurable mass changes.

SQ 11.4.6 Where are mass-energy changes found to be exactly in accordance with Einstein's equation?

Answer

Energy and mass changes in nuclear reactions are found to be exactly in accordance with these equations.

TOPIC 5 Space-Time Relativity

SQ 11.5.1 Define space.

Definition

Space is a three-dimensional extent in which all objects and events occur. It provides a framework to define the position and motion of various objects under the influence of some force.

SQ 11.5.2 How is time treated in the theory of relativity?

Answer

Time measures the sequence and duration of events. In the theory of relativity time is not absolute; it is considered the fourth dimension.

SQ 11.5.3 Give examples showing the role of time.

Examples

Oscillatory motion, such as that of a swinging pendulum, relies on time to determine the frequency of oscillations.
Time dilation, where time passes more slowly for an observer moving at extremely high speeds compared to one at rest.

SQ 11.5.4 What is space-time?

Definition

Spacetime is a mathematical model that unifies space and time into a single continuum. It is a concept used to describe all points of space and time and their relation to each other.

SQ 11.5.5 When is space-time curved?

Answer

According to Einstein's theory, space-time is curved especially near massive bodies and for speeds approaching the speed of light.

SQ 11.5.6 Explain the curvature of space-time using the fabric sheet analogy.

Analogy

Space-time can be hypothetically visualized as a fabric sheet. If a heavy ball is placed over this sheet, it curves.

Result

Objects such as stars and planets cause space-time to curve around themselves, and the more massive the object the deeper the curve.

SQ 11.5.7 How does Einstein's theory describe gravity?

Answer

We do not speak of a force of gravity acting on bodies. Instead, bodies and light rays move along geodesics, which are analogous to straight lines in plane geometry, in curved space-time.

SQ 11.5.8 Why is Einstein's theory considered an advancement over Newton's?

Reason

Newton discovered the inverse square law of gravity but offered no explanation for why gravity should follow this law. Einstein's theory also gives an inverse square law but explains why this is so.

SQ 11.5.9 Does Einstein's theory contradict Newton's laws?

Answer

No. Einstein's theory encompasses Newton's theory and yields the same results in all but very strong gravitational fields.

SQ 11.5.10 How was the bending of starlight confirmed?

Answer

The bending of starlight caused by the Sun's gravity was measured during a solar eclipse in 1919. The results matched Einstein's theory rather than Newton's, leading to Einstein's theory being hailed as a scientific triumph.

SQ 11.5.11 What angle of bending of starlight did Einstein predict?

Answer

Einstein predicted that the deflection would be 1.745 seconds of angle, which was found to be the same during the solar eclipse of 1919.

SQ 11.5.12 How did the detection of gravitational waves support Einstein's theory?

Answer

Gravitational waves are produced by celestial events causing disturbances, that is squeezes and stretches, in the curvature of space-time. These waves were detected in 2015 and announced in 2016.