Core topics

15 hours

Essential idea: Einstein's study of electromagnetism revealed inconsistencies between the theory of Maxwell and Newton's mechanics. He recognized that both theories could not be reconciled and so choosing to trust Maxwell's theory of electromagnetism he was forced to change long-cherished ideas about space and time in mechanics.

A.1 – The beginnings of relativity

Nature of science:

Paradigm shift: The fundamental fact that the speed of light is constant for all inertial observers has far-reaching consequences about our understanding of space and time. Ideas about space and time that went unchallenged for more than 2,000 years were shown to be false. The extension of the principle of relativity to accelerated frames of reference leads to the revolutionary idea of general relativity that the mass and energy that spacetime contains determines the geometry of spacetime. (2.3)

Understandings:

- Reference frames
- Galilean relativity and Newton's postulates concerning time and space
- Maxwell and the constancy of the speed of light
- Forces on a charge or current

Applications and skills:

- Using the Galilean transformation equations
- Determining whether a force on a charge or current is electric or magnetic in a given frame of reference
- Determining the nature of the fields observed by different observers

Theory of knowledge:

- When scientists claim a new direction in thinking requires a paradigm shift in how we observe the universe, how do we ensure their claims are valid?

Aims:

- **Aim 3:** this sub-topic is the cornerstone of developments that followed in relativity and modern physics

A.1 – The beginnings of relativity	
Guidance: • Maxwell's equations do not need to be described • Qualitative treatment of electric and magnetic fields as measured by observers in relative motion. Examples will include a charge moving in a magnetic field or two charged particles moving with parallel velocities. Students will be asked to analyse these motions from the point of view of observers at rest with respect to the particles and observers at rest with respect to the magnetic field. **Data booklet reference:** • $x' = x - vt$ • $u' = u - v$	

Essential idea: Observers in relative uniform motion disagree on the numerical values of space and time coordinates for events, but agree with the numerical value of the speed of light in a vacuum. The Lorentz transformation equations relate the values in one reference frame to those in another. These equations replace the Galilean transformation equations that fail for speeds close to that of light.

<table>
<tr><th colspan="2">A.2 – Lorentz transformations</th></tr>
<tr><td colspan="2">Nature of science:

Pure science: Einstein based his theory of relativity on two postulates and deduced the rest by mathematical analysis. The first postulate integrates all of the laws of physics including the laws of electromagnetism, not only Newton's laws of mechanics. (1.2)</td></tr>
<tr><td>Understandings:
• The two postulates of special relativity
• Clock synchronization
• The Lorentz transformations
• Velocity addition
• Invariant quantities (spacetime interval, proper time, proper length and rest mass)
• Time dilation
• Length contraction
• The muon decay experiment
Applications and skills:
• Using the Lorentz transformations to describe how different measurements of space and time by two observers can be converted into the measurements observed in either frame of reference
• Using the Lorentz transformation equations to determine the position and time coordinates of various events
• Using the Lorentz transformation equations to show that if two events are simultaneous for one observer but happen at different points in space, then the events are not simultaneous for an observer in a different reference frame
• Solving problems involving velocity addition
• Deriving the time dilation and length contraction equations using the Lorentz equations</td>
<td>Utilization:
• Once a very esoteric part of physics, relativity ideas about space and time are needed in order to produce accurate global positioning systems (GPS)
Aims:
• Aim 2: the Lorentz transformation formulae provide a consistent body of knowledge that can be used to compare the description of motion by one observer to the description of another observer in relative motion to the first
• Aim 3: these formulae can be applied to a varied set of conditions and situations
• Aim 9: the introduction of relativity pushed the limits of Galilean thoughts on space and motion</td></tr>
</table>

A.2 – Lorentz transformations

- Solving problems involving time dilation and length contraction
- Solving problems involving the muon decay experiment

Guidance:

- Problems will be limited to one dimension
- Derivation of the Lorentz transformation equations will not be examined
- Muon decay experiments can be used as evidence for both time dilation and length contraction

Data booklet reference:

- $\gamma = \dfrac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}}$
- $x' = \gamma(x - vt);\ \Delta x' = \gamma(\Delta x - v\Delta t)$
- $t' = \gamma\left(t - \dfrac{vx}{c^2}\right);\ \Delta t' = \gamma\left(\Delta t - \dfrac{v\Delta x}{c^2}\right)$
- $u' = \dfrac{u - v}{1 - \dfrac{uv}{c^2}}$
- $\Delta t = \gamma \Delta t_0$
- $L = \dfrac{L_0}{\gamma}$
- $(ct')^2 - (x')^2 = (ct)^2 - (x)^2$

Essential idea: Spacetime diagrams are a very clear and illustrative way to show graphically how different observers in relative motion to each other have measurements that differ from each other.

<table>
<tr><th colspan="2">A.3 – Spacetime diagrams</th></tr>
<tr><td colspan="2">Nature of science:
Visualization of models: The visualization of the description of events in terms of spacetime diagrams is an enormous advance in understanding the concept of spacetime. (1.10)</td></tr>
<tr><td>Understandings:
• Spacetime diagrams
• Worldlines
• The twin paradox
Applications and skills:
• Representing events on a spacetime diagram as points
• Representing the positions of a moving particle on a spacetime diagram by a curve (the worldline)
• Representing more than one inertial reference frame on the same spacetime diagram
• Determining the angle between a worldline for specific speed and the time axis on a spacetime diagram
• Solving problems on simultaneity and kinematics using spacetime diagrams
• Representing time dilation and length contraction on spacetime diagrams
• Describing the twin paradox
• Resolving of the twin paradox through spacetime diagrams</td><td>Theory of knowledge:
• Can paradoxes be solved by reason alone, or do they require the utilization of other ways of knowing?
Aims:
• Aim 4: spacetime diagrams allow one to analyse problems in relativity more reliably</td></tr>
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A.3 – Spacetime diagrams	
Guidance: • Examination questions will refer to spacetime diagrams; these are also known as Minkowski diagrams • Quantitative questions involving spacetime diagrams will be limited to constant velocity • Spacetime diagrams can have t or ct on the vertical axis • Examination questions may use units in which $c = 1$ **Data booklet reference:** • $\theta = \tan^{-1}\left(\frac{v}{c}\right)$	

Additional higher level option topics

10 hours

Essential idea: The relativity of space and time requires new definitions for energy and momentum in order to preserve the conserved nature of these laws.

A.4 – Relativistic mechanics

Nature of science:

Paradigm shift: Einstein realized that the law of conservation of momentum could not be maintained as a law of physics. He therefore deduced that in order for momentum to be conserved under all conditions, the definition of momentum had to change and along with it the definitions of other mechanics quantities such as kinetic energy and total energy of a particle. This was a major paradigm shift. (2.3)

Understandings:

- Total energy and rest energy
- Relativistic momentum
- Particle acceleration
- Electric charge as an invariant quantity
- Photons
- MeV c^{-2} as the unit of mass and MeV c^{-1} as the unit of momentum

Applications and skills:

- Describing the laws of conservation of momentum and conservation of energy within special relativity
- Determining the potential difference necessary to accelerate a particle to a given speed or energy
- Solving problems involving relativistic energy and momentum conservation in collisions and particle decays

Theory of knowledge:

- In what ways do laws in the natural sciences differ from laws in economics?

Utilization:

- The laws of relativistic mechanics are routinely used in order to manage the operation of nuclear power plants, particle accelerators and particle detectors

Aims:

- **Aim 4:** relativistic mechanics synthesizes knowledge on the behaviour of matter at speeds close to the speed of light
- **Aim 9:** the theory of relativity imposes one severe limitation: nothing can exceed the speed of light

A.4 – Relativistic mechanics	
Guidance: • Applications will involve relativistic decays such as calculating the wavelengths of photons in the decay of a moving pion $[\pi^{o} \rightarrow 2\gamma]$ • The symbol m_0 refers to the *invariant rest mass* of a particle • The concept of a relativistic mass that varies with speed will not be used • Problems will be limited to one dimension **Data booklet reference:** • $E = \gamma m_0 c^2$ • $E_0 = m_0 c^2$ • $E_K = (\gamma - 1) m_0 c^2$ • $p = \gamma m_0 \upsilon$ • $E^2 = p^2 c^2 + m_0^2 c^4$ • $qV = \Delta E_K$	

Essential idea: General relativity is applied to bring together fundamental concepts of mass, space and time in order to describe the fate of the universe.

A.5 – General relativity

Nature of science:

Creative and critical thinking: Einstein's great achievement, the general theory of relativity, is based on intuition, creative thinking and imagination, namely to connect the geometry of spacetime (through its curvature) to the mass and energy content of spacetime. For years it was thought that nothing could escape a black hole and this is true but only for classical black holes. When quantum theory is taken into account a black hole radiates like a black body. This unexpected result revealed other equally unexpected connections between black holes and thermodynamics. (1.4)

Understandings:

- The equivalence principle
- The bending of light
- Gravitational redshift and the Pound–Rebka–Snider experiment
- Schwarzschild black holes
- Event horizons
- Time dilation near a black hole
- Applications of general relativity to the universe as a whole

Applications and skills:

- Using the equivalence principle to deduce and explain light bending near massive objects
- Using the equivalence principle to deduce and explain gravitational time dilation
- Calculating gravitational frequency shifts
- Describing an experiment in which gravitational redshift is observed and measured
- Calculating the Schwarzschild radius of a black hole
- Applying the formula for gravitational time dilation near the event horizon of a black hole

Theory of knowledge:

- Although Einstein self-described the cosmological constant as his "greatest blunder", the 2011 Nobel Prize was won by scientists who had proved it to be valid through their studies on dark energy. What other examples are there of initially doubted claims being proven correct later in history?

Utilization:

- For the global positioning system to be so accurate, general relativity must be taken into account in calculating the details of the satellite's orbit
- The development of the general theory of relativity has been used to explain the very large-scale behaviour of the universe as a whole with far-reaching implications about the future development and fate of the universe

Aims:

- **Aim 2:** the general theory of relativity is a great synthesis of ideas that are required to describe the large-scale structure of the universe
- **Aim 9:** it must be appreciated that the magnificent Newtonian structure had serious limitations when it came to the description of very detailed aspects of planetary motion

A.5 – General relativity	
Guidance: • Students should recognize the equivalence principle in terms of accelerating reference frames and freely falling frames **Data booklet reference:** • $\frac{\Delta f}{f} = \frac{g\Delta h}{c^2}$ • $R_s = \frac{2GM}{c^2}$ • $\Delta t = \frac{\Delta t_0}{\sqrt{1 - \frac{R_S}{r}}}$	