

## 9.2.4 Special Relativity

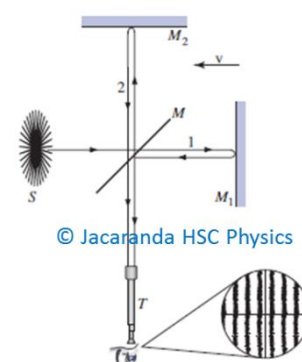
Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

### 4.1 Outline the features of the **aether model for the transmission of light**

- Aether: proposed **medium of light** and electromagnetic waves (as waves require a **medium**)
  - **Undetectable** (thin, transparent)
  - Filled all space, low **density**, perfectly **elastic**
  - **Permeated** (spread throughout) all matter, **permeable** to all matter

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

- Aim of experiment was to **detect the velocity of the Earth through** the aether using light
  - Two light rays sent towards and across aether wind
  - Apparatus swung **90° to swap ray direction**
- Interference pattern was observed with the **interferometer**, if they were the same for both 0° and 90°, there would be **no change** in pattern
- Therefore, aether model was **invalid theory** as there was no evidence for existence of aether



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

- **James Clerk Maxwell** – nature of light needing a medium, aether
- **1887: Michelson-Morley** showed that there was an absence of aether
  - **1905: Einstein** published theory of special relativity
- Scepticism and acceptance of theories debated
  - Initially, Michelson-Morley experiments **were ignored and aether theory was adapted**
  - **After Einstein** showed aether was not required, belief on aether faded

### 4.4 Outline the nature of **inertial frames of reference**

- Frame of **reference**: Anything **with respect to** which we **describe motion** and take measurements
  - Motion is **different** based on different perspectives/frames of reference
  - **Inertial** frame of reference: non-accelerating (**constant or no motion**) frame of reference
- When moving at a constant velocity, objects interact the **same way as if not moving**
  - E.g. a ball will fall to the ground and will not move sideways
  - Not able to identify if the frame is stationary or moving
- **Non-inertial** frame of reference: acceleration/deceleration

#### 4.5 Discuss the **principle of relativity**

- Velocity of light has a **constant value of  $c$** , regardless of **relative motion** of source or observer
- **All inertial frames of reference are equal/relative** and no inertial frame of reference is **truer**
  - There is **no fixed, absolute frame of reference** to which all motions could be compared

#### 4.6 Describe the **significance** of Einstein's assumption of the **constancy of the speed of light**

- **Michelson-Morley's 'null' result** can be explained
  - Aether concept not required, and there is no absolute frame of reference

#### 4.7 Identify that if **$c$ is constant** then **space and time become relative**

- Speed of light,  $c$ , is measured using **distance and time**
- If  $c$  is constant, **distance and time must change** (i.e. become relative)
  - E.g. a person in a spacecraft will always see the speed of light as  $c$ , even when velocity changes

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

- Original metre standard:  $1 \times 10^{10-7}$  of distance from north pole to the equator
- Now defined by **length of path travelled by light in a vacuum** over  $1/299792458^{\text{th}}$  of a second
  - Based on speed of light as it is a **constant**

#### 4.9 Explain **qualitatively and quantitatively** the **consequence of special relativity** in relation to:

##### THE RELATIVITY OF **SIMULTANEITY**

- **Relativity of simultaneity**: two events simultaneous to one observer **may not appear simultaneous** to another observer in another frame of reference
- 'Thought experiment' – **light from two ends** of the train
  - One observer standing equally distanced from both ends will see both lights turn on at the same time
    - Time taken for front light  $t = \frac{d}{c}$  while the back light  $t' = \frac{d'}{c}$
    - Since observer is equally distanced,  $d = d'$  and so  $t = t'$
  - Second observer is **in a different frame of reference** in the middle of the **train** travelling at  $v$ 
    - Time taken for front light  $t = \frac{d+vt}{c}$  while the back light  $t' = \frac{d'-vt}{c}$
    - Since  $d = d'$ ,  $t' > t$  and so they will see the **front light before the back light**
- Therefore there is no **truer** inertial frame of reference

Example: Train

## THE EQUIVALENCE BETWEEN MASS AND ENERGY

- Energy and mass are **convertible** based on:

$$E = mc^2$$

Where E = energy (J), m = mass (kg), c = speed of light ( $3 \times 10^8 \text{ms}^{-1}$ )

- Explains the **Law of Conservation of Mass and Energy** – can only be transformed not destroyed
- Theory extended to creating large amounts of energy from mass – nuclear

## LENGTH CONTRACTION

- **Length contraction**: length of a **moving object appears shorter** to length at rest
  - Only occurs in dimension of direction of motion
- Similarly explained by proving **time dilation** (below)

$$l_v = l_o \sqrt{1 - \frac{v^2}{c^2}}$$

Where  $l_v$  = moving length (m),  $l_o$  = length at rest (m),  $v$  = relative velocity ( $\text{ms}^{-1}$ ),  $c$  = speed of light

## TIME DILATION

- **Time dilation**: time **runs slower** (time interval increased) when moving
- ‘Thought experiment’ – **light clock** on a moving train
  - One observer inside the train, sees light moving up and down
    - Time taken for light to go up and down  $t_o = \frac{2d}{c}$
  - Second observer outside train, sees light moving sideways, time taken  $t_v = \frac{2d'}{c}$
  - Since  $d' > d$ , then time  $t_v > t_o$ , so time is lengthened when observing train

$$t_v = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Where  $t_o$  = rest time (relatively stationary) (s),  $t_v$  = moving time (s),  $v$  = velocity of frame ( $\text{ms}^{-1}$ )

## MASS DILATION

- **Mass dilation**: mass of moving object is **greater** than mass at rest
- ‘Thought experiment’ – two spacecraft collision with momentum calculated

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

$m_v$  = mass when stationary (kg),  $m_o$  = moving mass (kg),  $v$  = relative velocity ( $\text{ms}^{-1}$ )

#### 4.10 Discuss the **implications** of mass increase, time dilation and length contraction **for space travel**

- As a spacecraft moves towards c:
  - **Mass increases** and therefore it becomes **harder to accelerate (due to its mass)**
  - Time dilates, so **prolonged space travel** is possible, and **time will run slower** compared to Earth
    - However, if pilot returns, **there is a change in velocity** – becomes a non-inertial frame
  - **Distance** decreases, and spacecraft path will **appear shorter** than measured on Earth
    - Note: time is also running slower, so they still cover same distance over time

#### 4.P1 Gather and process information to interpret the **results of the Michelson-Morley experiment**

- See 4.2
- The 'null' result of the Michelson-Morley experiment proved that there was **no aether**
  
- Aim of experiment was to **detect the velocity of the Earth through** the aether using light
  - Two light rays sent towards and across aether wind
  - Apparatus swung  $90^\circ$  **to swap ray direction**
- Interference pattern was observed with the **interferometer**, if they were the same for both  $0^\circ$  and  $90^\circ$ , there would be **no change** in pattern
- Therefore, aether model was **invalid theory** as there was no evidence for existence of aether