How fast is the fastest ?

Amol Dighe
Department of Theoretical Physics
Tata Institute of Fundamental Research

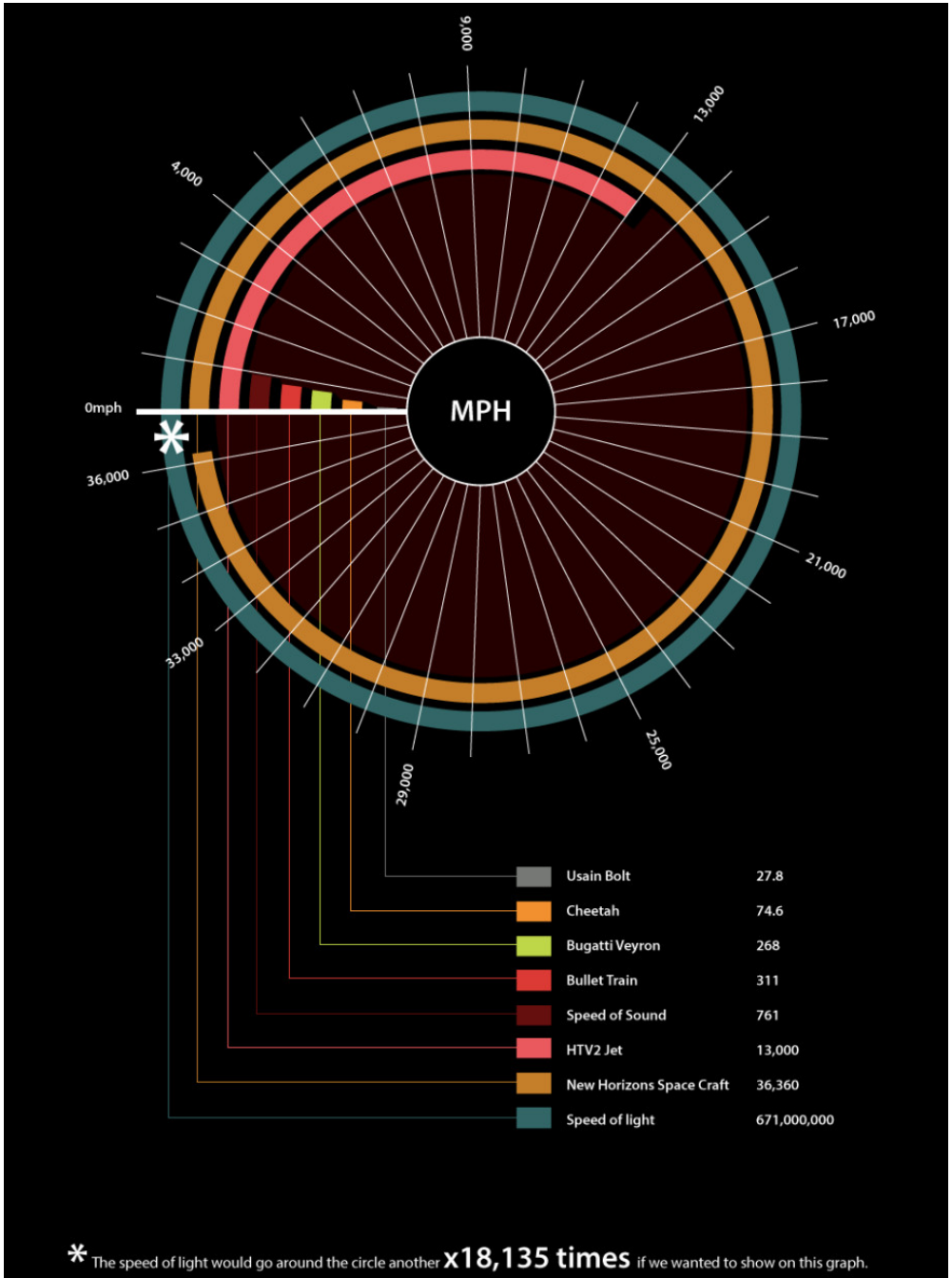
Chai-and-Why, Ruparel College, Oct 18, 2015

How fast is the fastest ?

1. What moves the fastest ?
2. How to measure such a large speed ?
3. Why is there even a single “the fastest” speed ?
4. Modern (20th-century) measurements of the speed
5. How to measure this speed at home

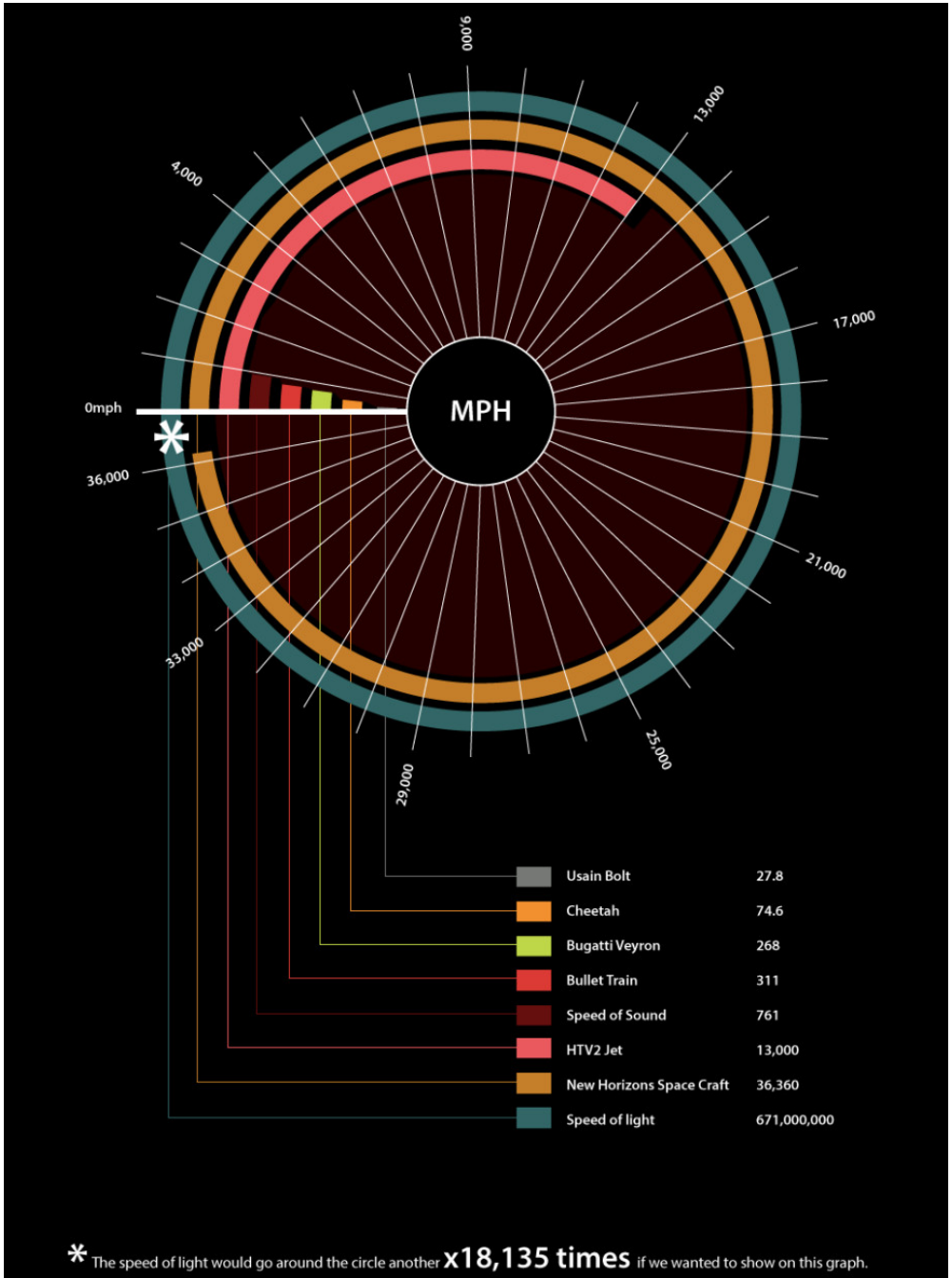
How fast is the fastest ?

The light *(travelling through vacuum)*



- Light would have gone around the track $\sim$ 18,000 times !

The light *(travelling through vacuum)*



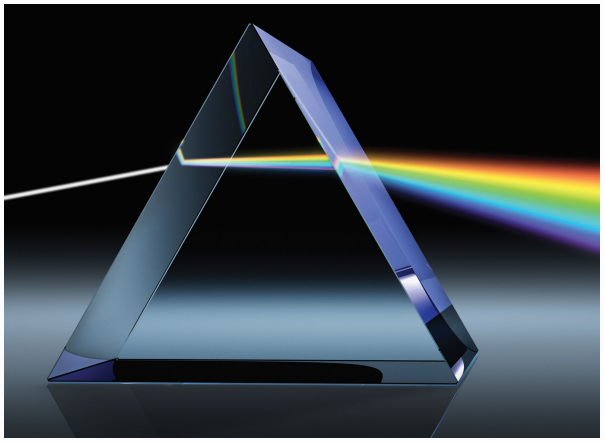
- Light would have gone around the track $\sim$ 18,000 times !

Some approximate idea of the speed

Speed of light in vacuum: about 3 lakh km/s

- Time to the sun: 8 minutes
- Time to the moon: 1 second
- Time to cross the earth: $\frac{1}{25}$ second
- Time to travel 1 foot: 1 nanosecond ($\frac{1}{1\ 000\ 000\ 000}$ second)

Light slows down in media..



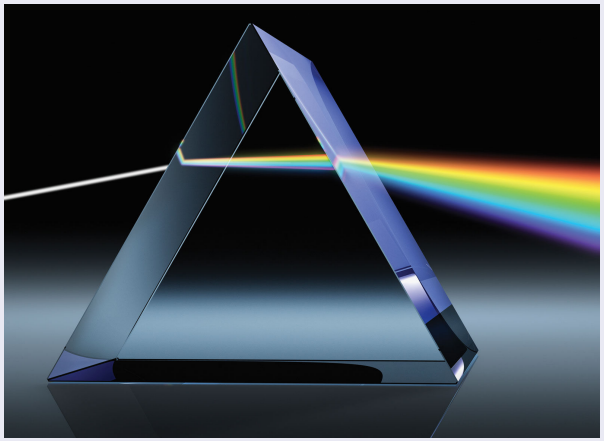
- Light speed reduces in glass to about 2 lakh km/s ($\sim$ 70%)
- The colours split because they travel at different speeds in glass

Some approximate idea of the speed

Speed of light in vacuum: about 3 lakh km/s

- Time to the sun: 8 minutes
- Time to the moon: 1 second
- Time to cross the earth: $\frac{1}{25}$ second
- Time to travel 1 foot: 1 nanosecond ($\frac{1}{1\ 000\ 000\ 000}$ second)

Light slows down in media..



- Light speed reduces in glass to about 2 lakh km/s ($\sim$ 70%)
- The colours split because they travel at different speeds in glass

How fast is the fastest ?

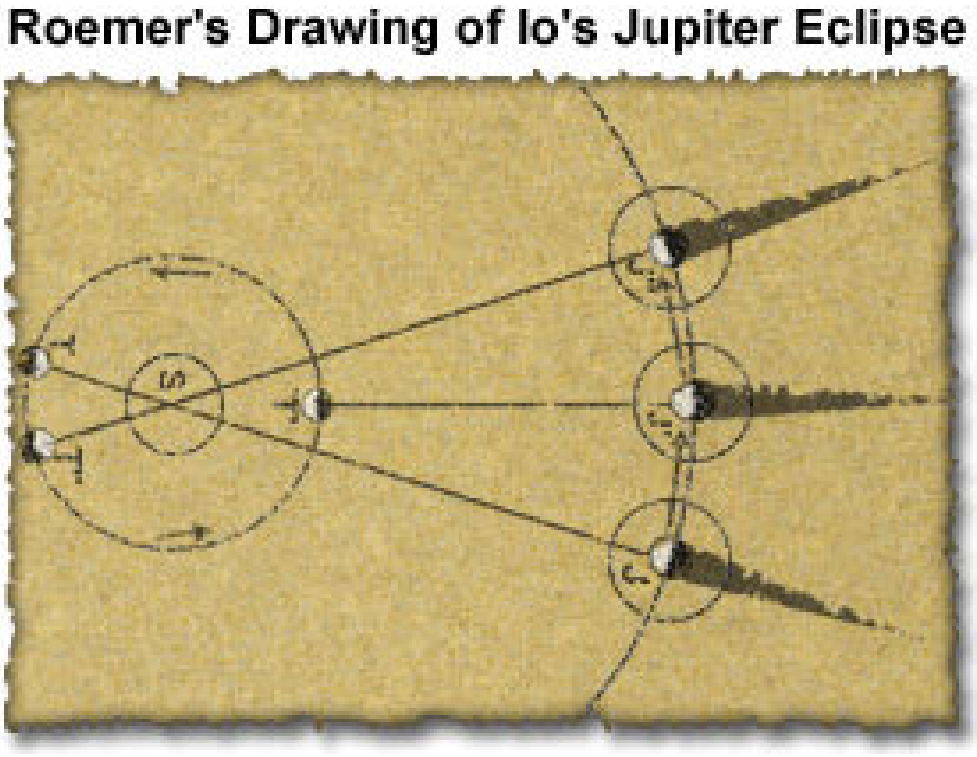
What's wrong with this ?

- Light would travel 3 km in only 0.00001 seconds
- Light speed is, practically speaking, infinity.

What's wrong with this ?

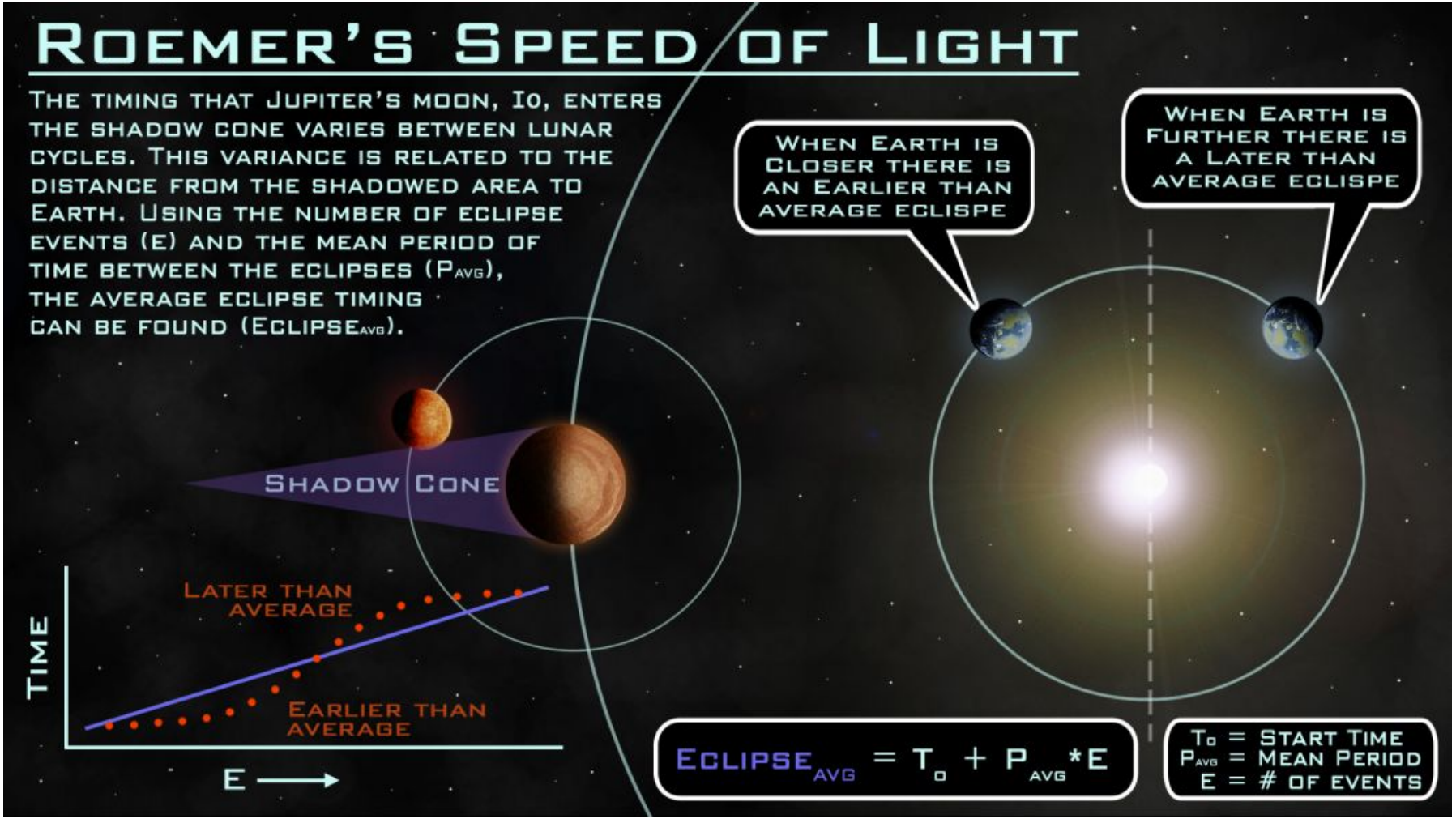
- Light would travel 3 km in only 0.00001 seconds
- Light speed is, practically speaking, infinity.

Eclipse of jupiter: Roemer 1676



- When earth is closer to jupiter, eclipses happen earlier
- When earth is away, eclipses happen later
- Light takes 22 minutes to cross the earth's orbit

Eclipse of jupiter: Roemer 1676

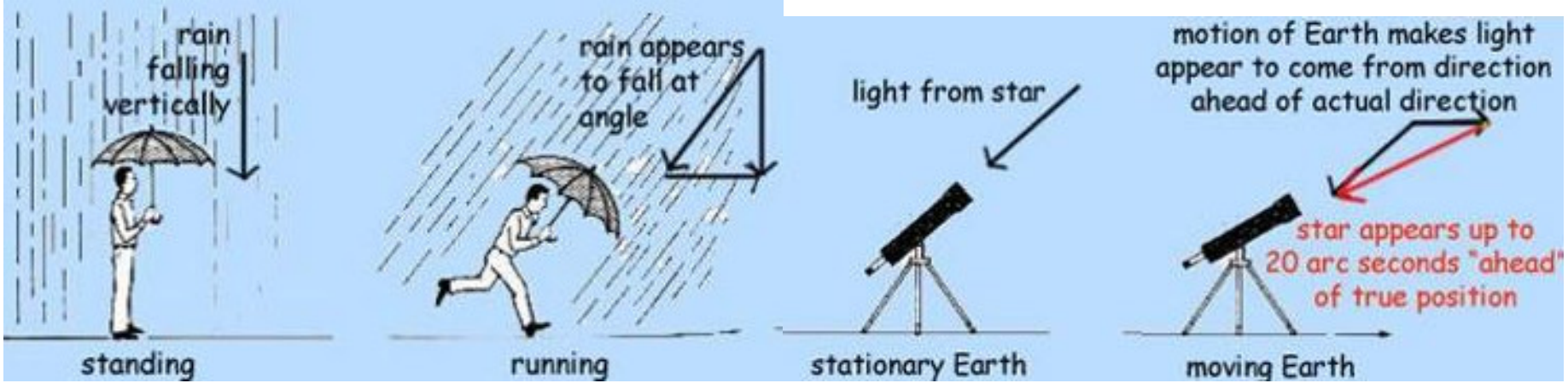


Roemer's light speed: 220 000 km/s

Aberration of stars: Bradley 1729

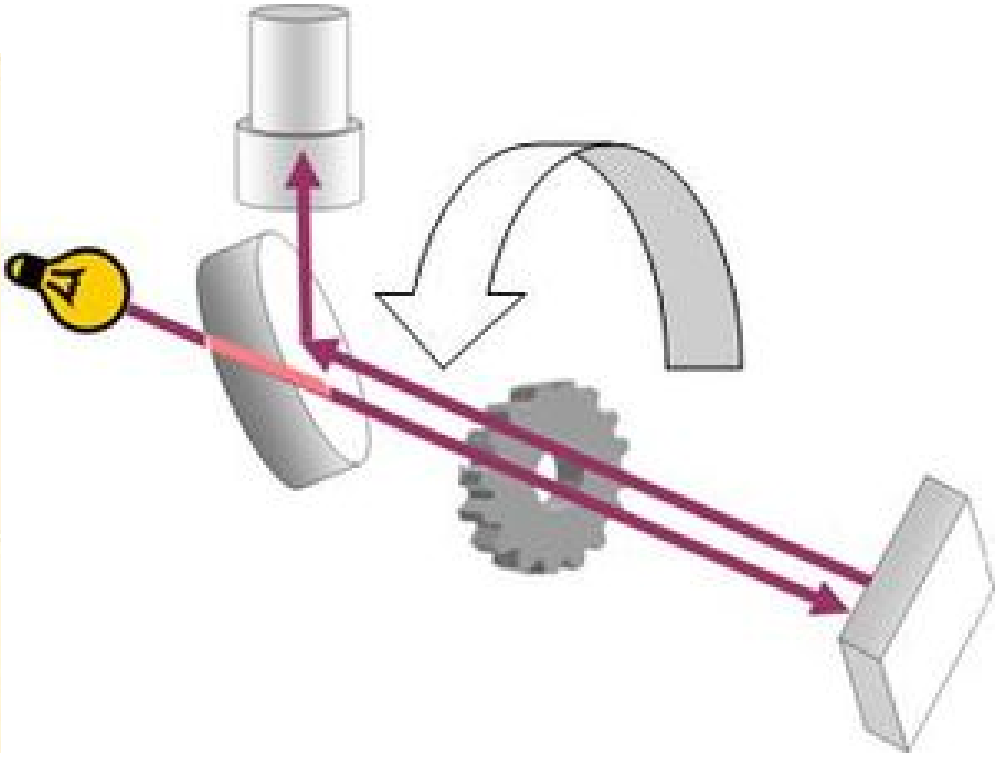
James Bradley
(1693-1762)

Observed small annual cyclic motion of a star: *Gamma Draconis*



Bradley speed of light: 301 000 km/s

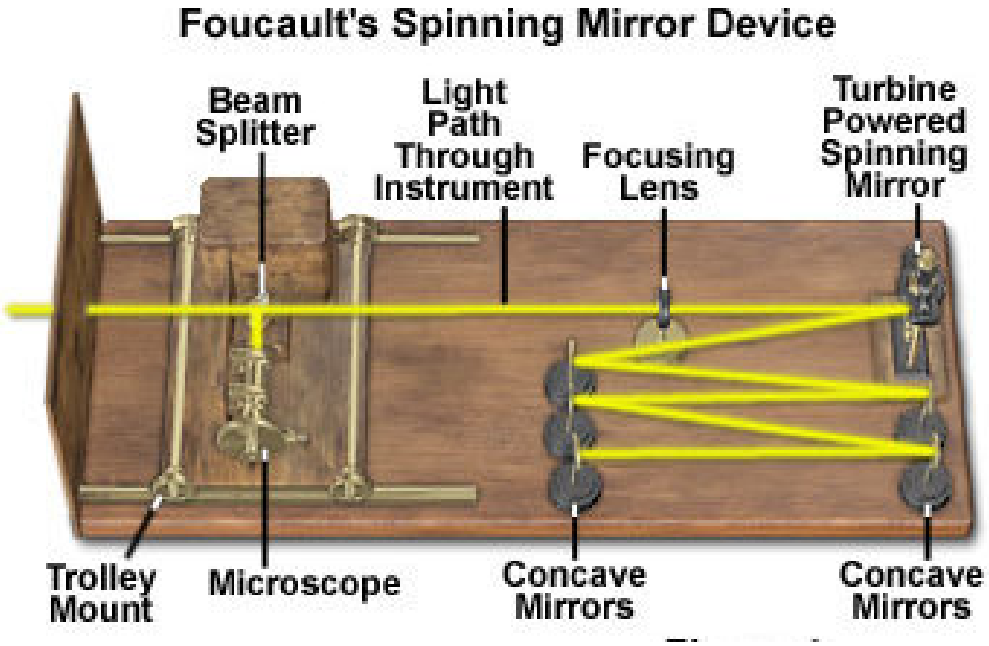
Cogwheel method: Fizeau 1849



- Mirror 8 km away
- Keep increasing the speed of cogwheel till
  Light enters from one gap, returns from the next
- Speed of light = distance / time

Fizeau's light speed: 315 000 km/s

Rotating mirror method: Foucault 1850



- Many reflections, so the apparatus can be shorter
- Time measurement was the most difficult part
- Still 1% accuracy obtained !

Focault's light speed: $(298\,000 \pm 500)$ km/s

How fast is the fastest ?

Speed depends on the speed of source

- Bullet shot from a gun, which is itself moving forwards (say on a train), travels faster when seen from the ground.
- Light emitted from a source moving in the same direction should travel faster when seen from outside.
- Faster the source, faster the speed of light
- There should not be a “fastest” speed

Speed depends on the speed of source

- Bullet shot from a gun, which is itself moving forwards (say on a train), travels faster when seen from the ground.
- Light emitted from a source moving in the same direction should travel faster when seen from outside.
- Faster the source, faster the speed of light
- There should not be a “fastest” speed

Speed depends on the speed of source

- Bullet shot from a gun, which is itself moving forwards (say on a train), travels faster when seen from the ground.
- Light emitted from a source moving in the same direction should travel faster when seen from outside.
- Faster the source, faster the speed of light
- There should not be a “fastest” speed

How to measure change in light speed due to source

Luminiferous ether: medium light travels through

- Earth moves through the Ether.
- The light should travel faster in the direction of movement of Earth, slower in the opposite direction.
- The speed of light cannot be the same in all directions !

Speeds of the earth

- Spinning about its axis: 0.5 km/s
- Revolution about the sun: 30 km/s
- Solar system around the milky way: 250 km/s
- Milky way around other nearby galaxies: 300 km/s

Need to measure speed of light to an accuracy of at least $\sim$ 300 km/s (i.e. 0.1 %)

How to measure change in light speed due to source

Luminiferous ether: medium light travels through

- Earth moves through the Ether.
- The light should travel faster in the direction of movement of Earth, slower in the opposite direction.
- The speed of light cannot be the same in all directions !

Speeds of the earth

- Spinning about its axis: 0.5 km/s
- Revolution about the sun: 30 km/s
- Solar system around the milky way: 250 km/s
- Milky way around other nearby galaxies: 300 km/s

Need to measure speed of light to an accuracy of at least $\sim$ 300 km/s (i.e. 0.1 %)

How to measure change in light speed due to source

Luminiferous ether: medium light travels through

- Earth moves through the Ether.
- The light should travel faster in the direction of movement of Earth, slower in the opposite direction.
- The speed of light cannot be the same in all directions !

Speeds of the earth

- Spinning about its axis: 0.5 km/s
- Revolution about the sun: 30 km/s
- Solar system around the milky way: 250 km/s
- Milky way around other nearby galaxies: 300 km/s

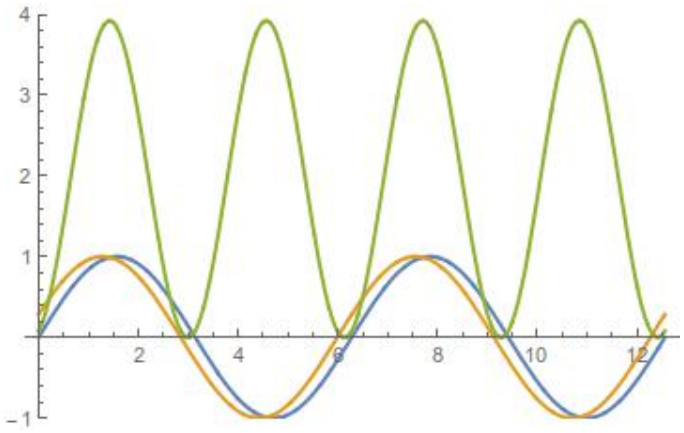
Need to measure speed of light to an accuracy of at least $\sim$ 300 km/s (i.e. 0.1 %)

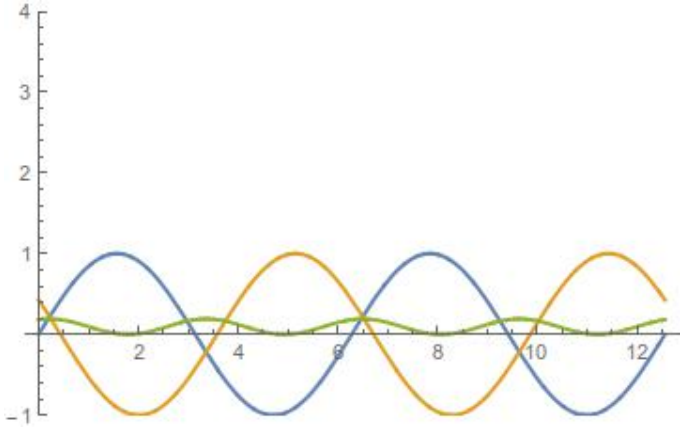
The “interference” trick

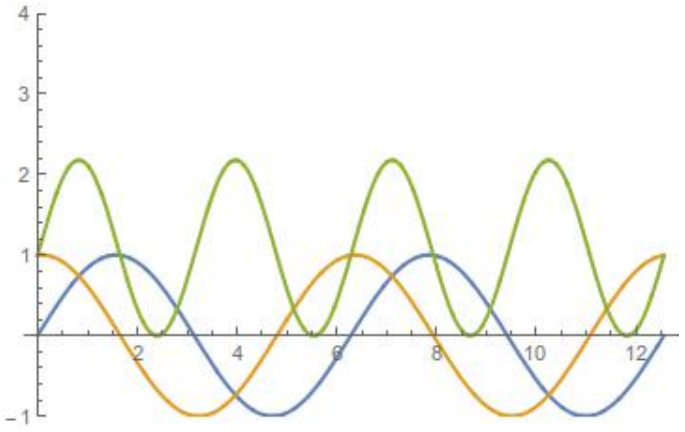
Interference: the principle

Intensity of the sum of two waves $\Rightarrow$

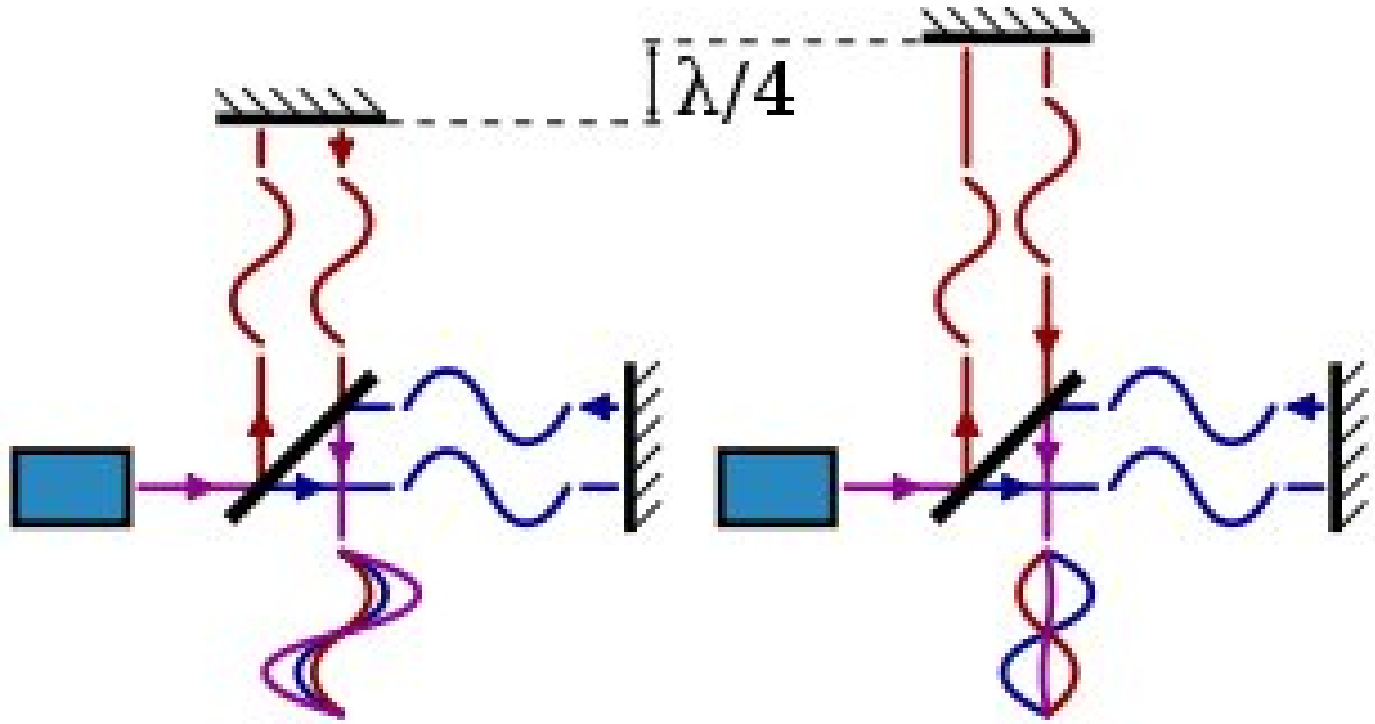
The phase difference between the waves





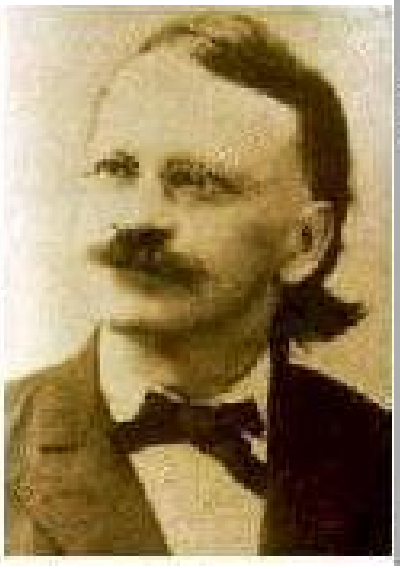


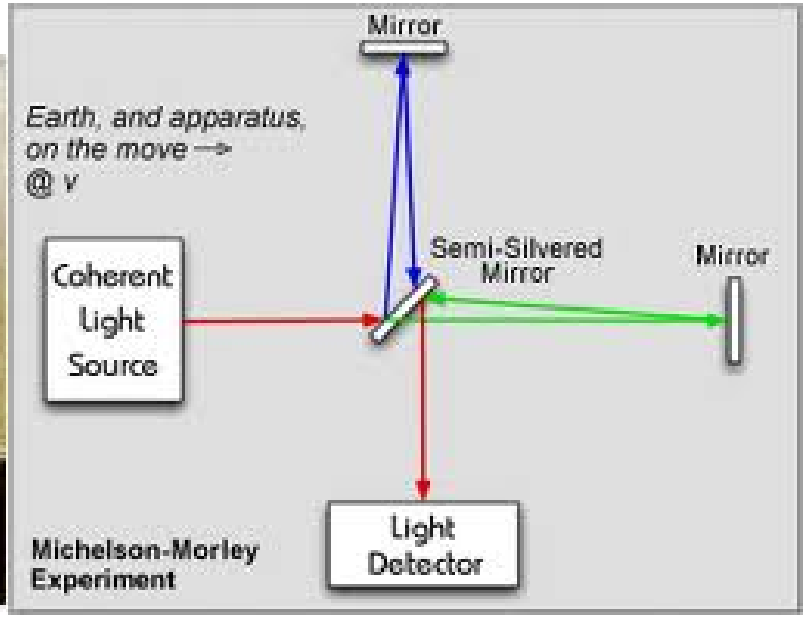
The interference experiment



- If distances travelled by two light rays are different, the interference pattern will be different.
- We are using the light wavelength ($\sim 500nm$) as a precise scale to measure distances !
- Note: measures difference in speeds precisely, not actual speeds

Michaelson-Morley experiment 1887

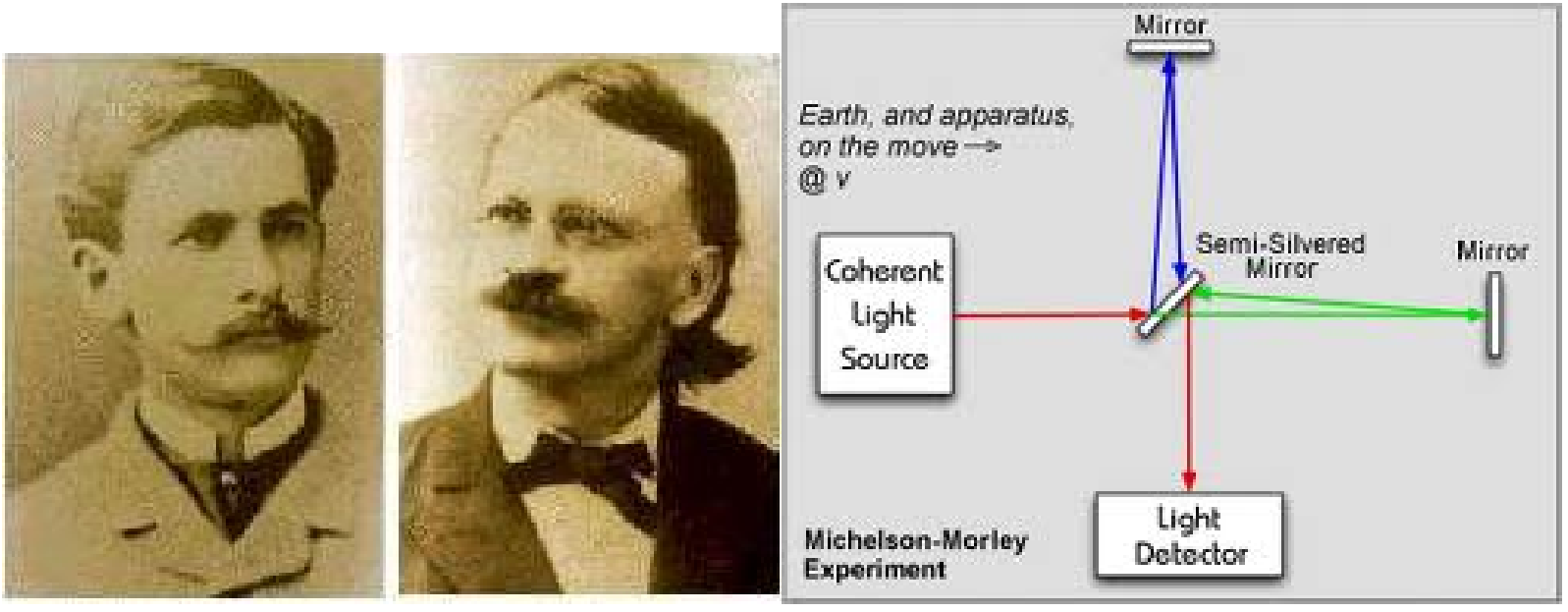




Shock of the century

- Speed of light along the earth's motion
  = Speed of light perpendicular to earth's motion
- A counter-intuitive result that revolutionised physics !

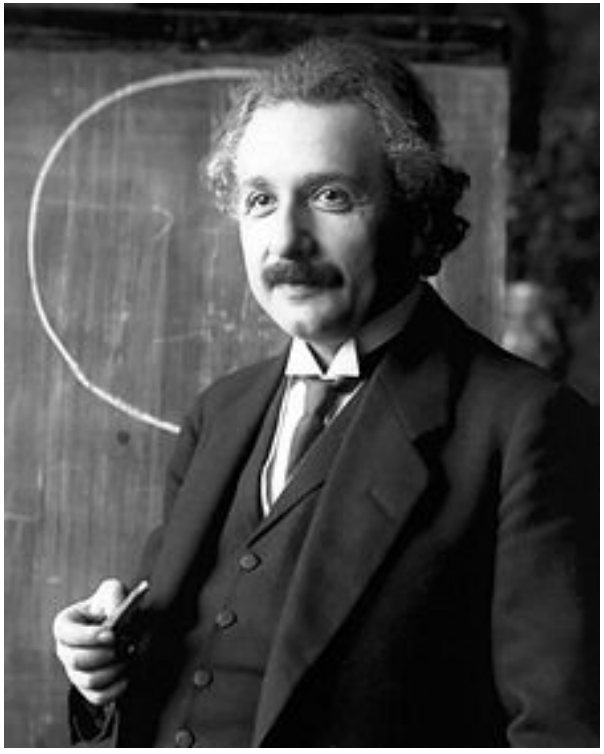
Michaelson-Morley experiment 1887



Shock of the century

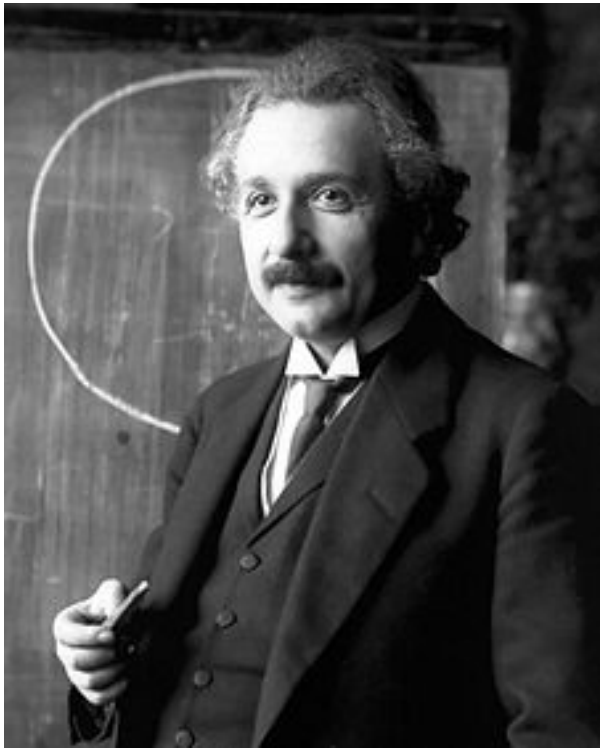
- Speed of light along the earth's motion
  = Speed of light perpendicular to earth's motion
- A counter-intuitive result that revolutionised physics !

Special Theory of relativity: Einstein, 1905



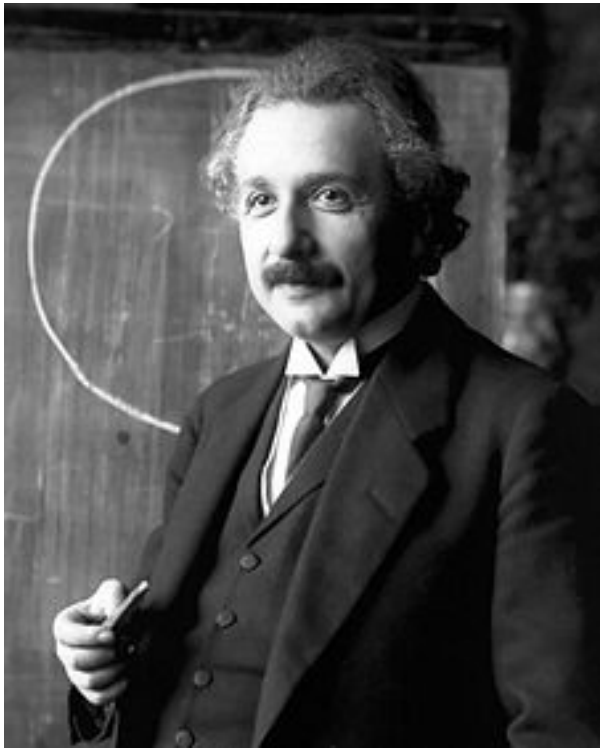
- Speed of light in vacuum the same for everyone
- Distances not the same for everyone
- Time not the same for everyone
- A consequence: No signal can travel faster than the speed of light in vacuum

Special Theory of relativity: Einstein, 1905



- Speed of light in vacuum the same for everyone
- Distances not the same for everyone
- Time not the same for everyone
- A consequence: No signal can travel faster than the speed of light in vacuum

Special Theory of relativity: Einstein, 1905



- Speed of light in vacuum the same for everyone
- Distances not the same for everyone
- Time not the same for everyone
- A consequence: No signal can travel faster than the speed of light in vacuum

Are we sure light is the fastest ?

- All speed measurements
- Cosmic rays coming from space
- High energy particles at particle acelerators
- All tests of Special Relativity

Moving light spots ? receding galaxies ? tacheons ?

Are we sure light is the fastest ?

- All speed measurements
- Cosmic rays coming from space
- High energy particles at particle acelerators
- All tests of Special Relativity

Moving light spots ? receding galaxies ? tacheons ?

How fast is the fastest ?

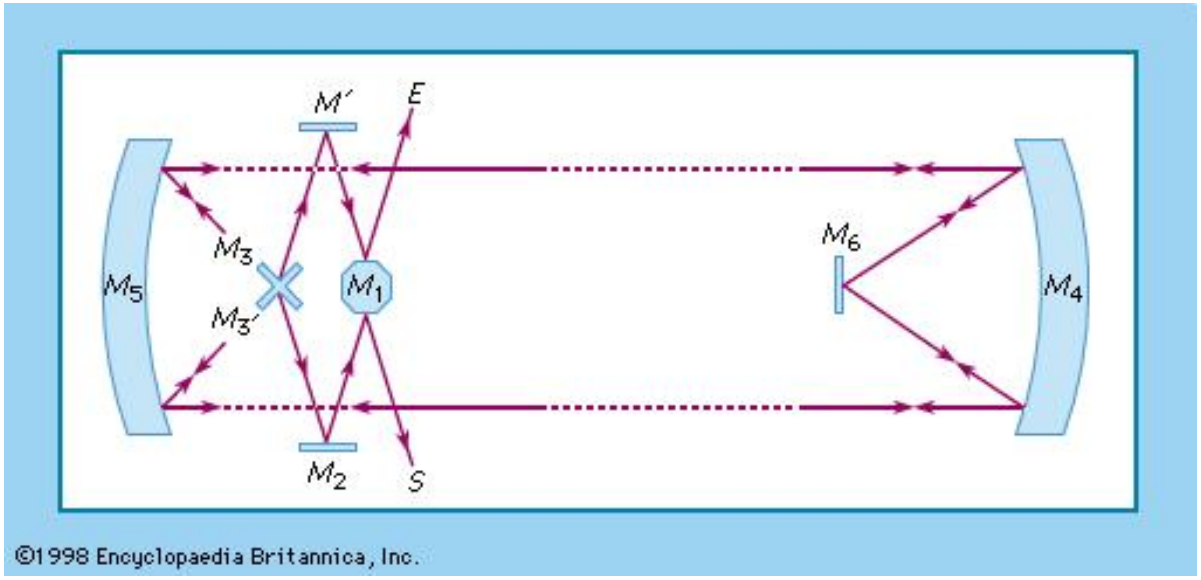
From capacitors: Rosa and Dorsay 1907

- Capacitances of simple geometries can be calculated theoretically
- These capacitances depend on the speed of light, $c = 1/\sqrt{\epsilon\mu}$
- Precision manufacture of capacitors and accurate measurements of their capacitances
  $\Rightarrow$ speed of light

Speed of light from capacitances: $(299\,710 \pm 30)$ km/s

Distance / time: Michelson 1926

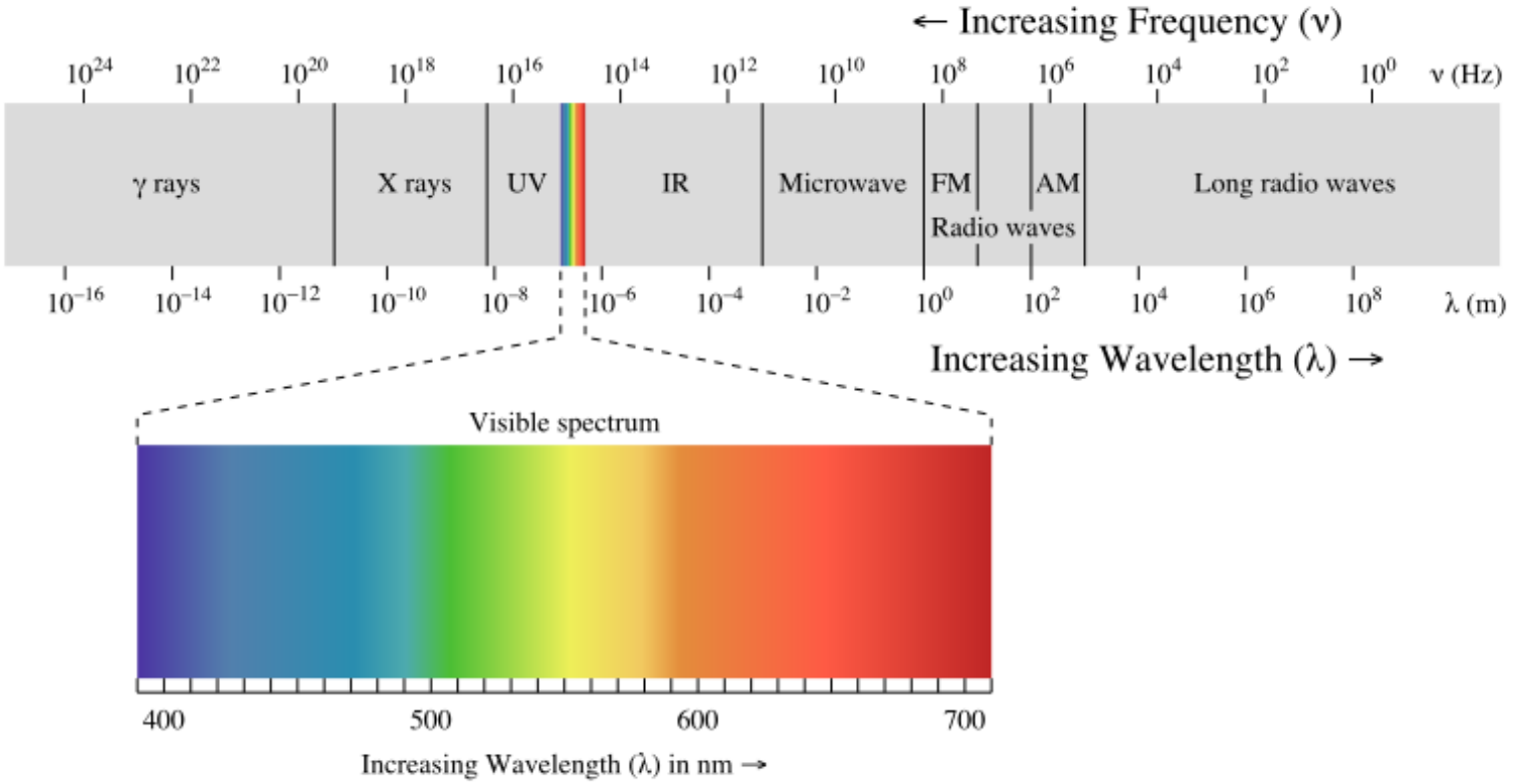
- Mount Wilson to Mount San Antonio : 22 miles $\times$ 2
- A rotating-mirror assembly



Michelson's speed of light: 299 796 km /s

Applies corrections for the refractive index of air !

Light as an electromagnetic wave



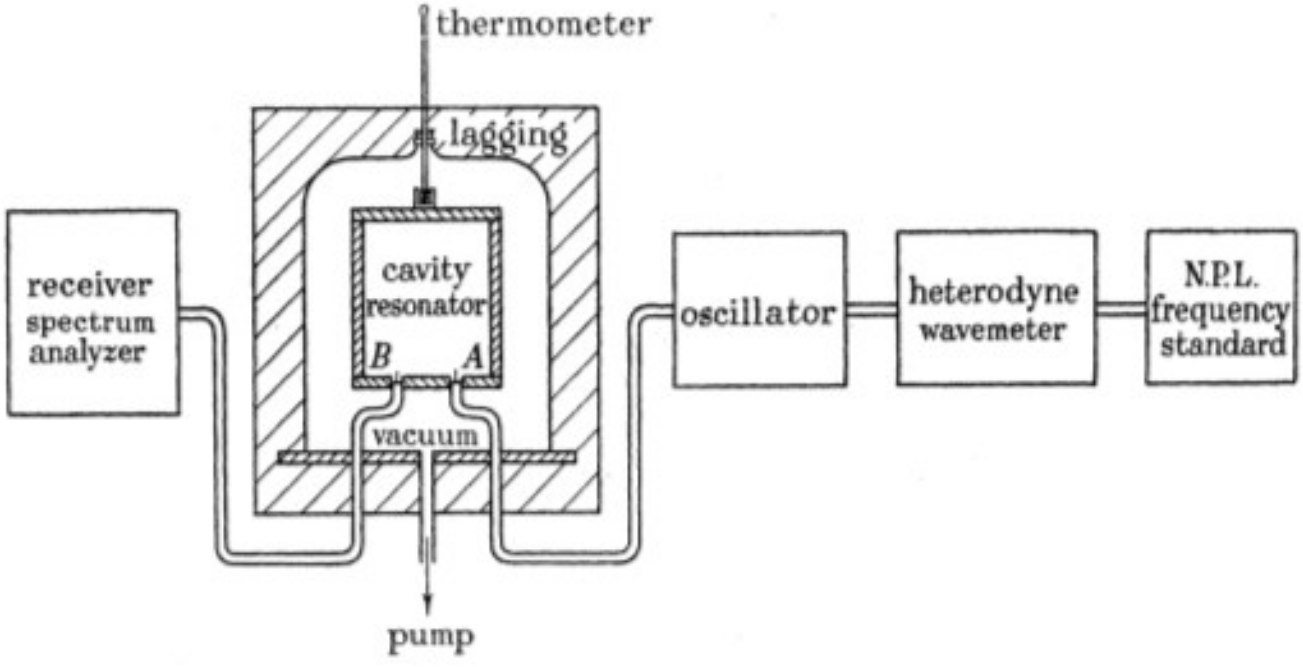
Measuring speed of any electromagnetic wave is the same as measuring the speed of light...

Resonance cavity: Essen and Gordan-Smith 1947

The velocity of propagation of electromagnetic waves derived from the resonant frequencies of a cylindrical cavity resonator

By L. Essen, D.Sc., Ph.D. and A. C. Gordon-Smith
The National Physical Laboratory

(*Communicated by Sir Charles Darwin, F.R.S.—Received 4 December* 1947)



Cavity speed of light: $(299\,792.5 \pm 3.0)$ km/s

Interferometry: Froome 1958, Evensen 1972

Radio interferometry: Froome 1958

Speed of light: 299 792.50 $\pm$ 0.1 km/s

Laser interferometry: Evensen 1972

Speed of light: 299 792.4562 $\pm$ 0.0011 km/s

The latest situation

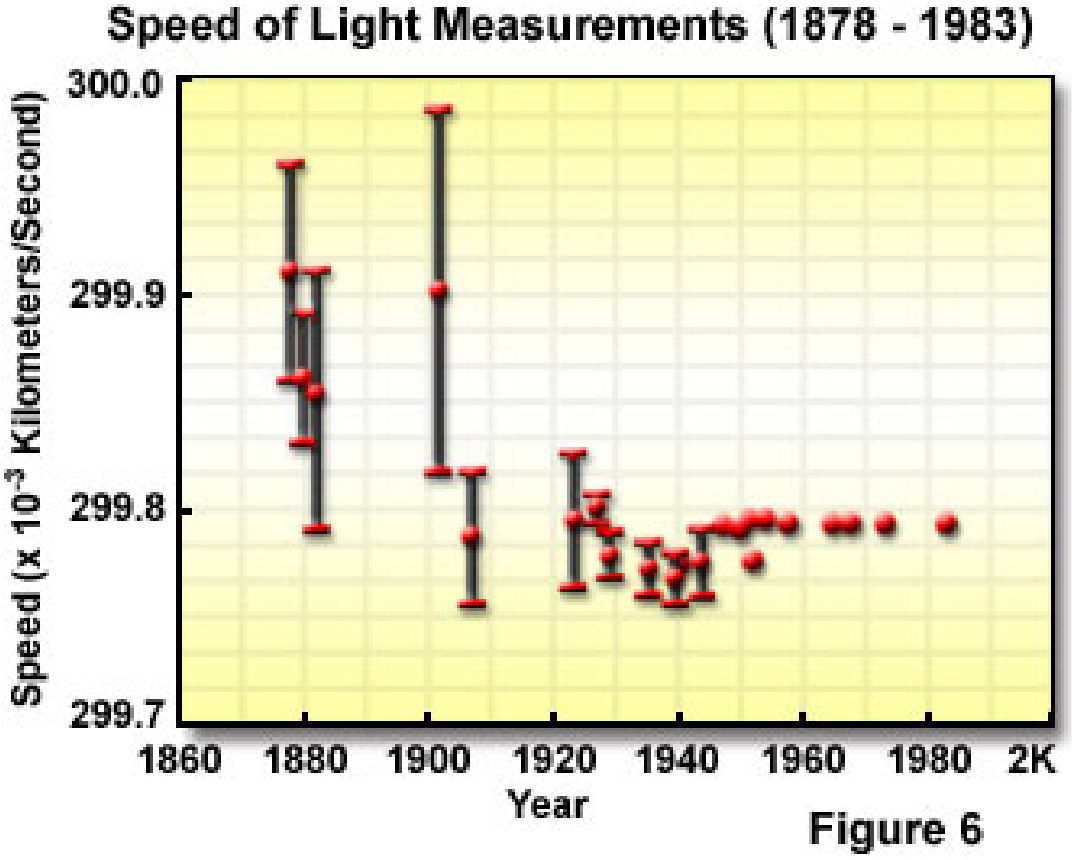


Figure 6

The tables have turned !

- Now we define meter using speed of light and time !
- *The metre is the length of the path travelled by light in vacuum during a time interval of 1/(299 792 458) of a second.*

The latest situation

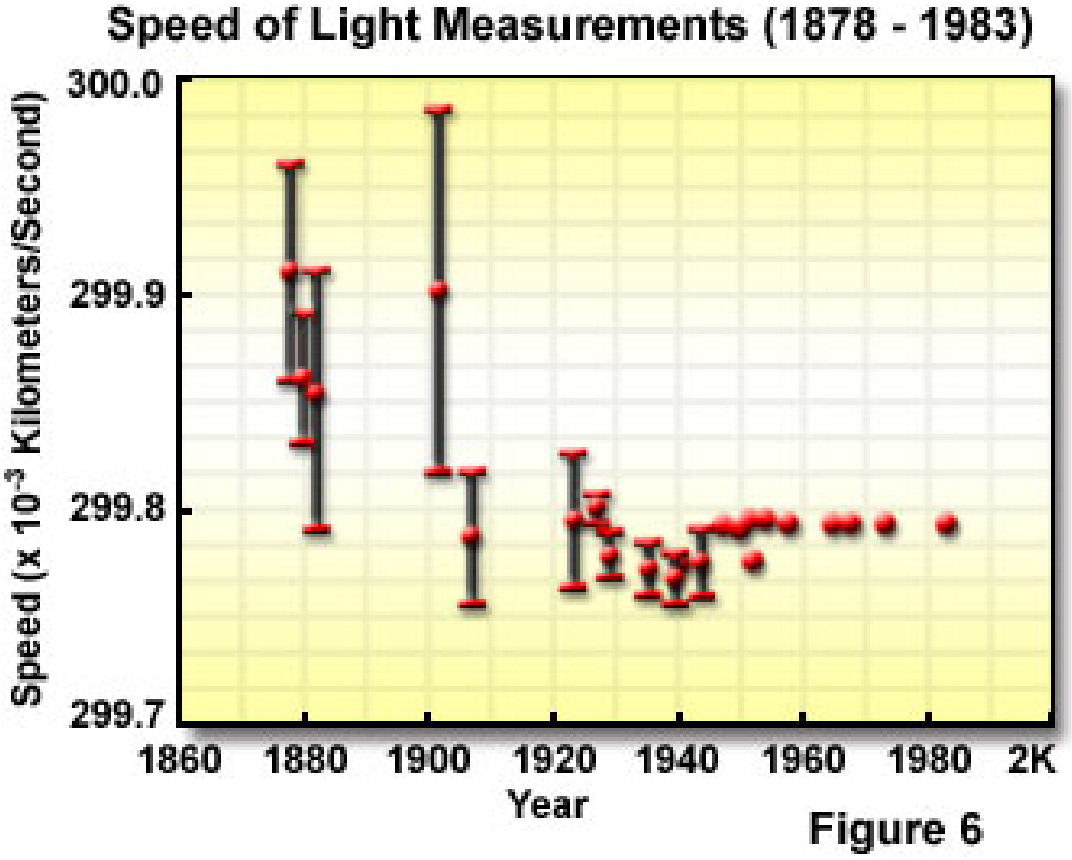


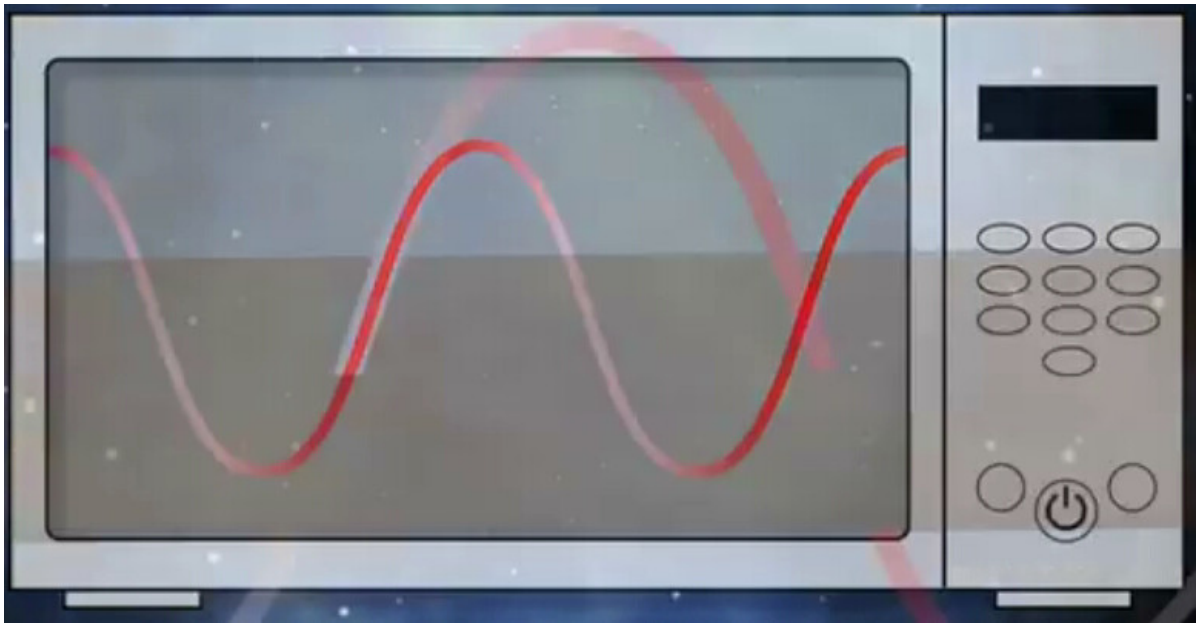
Figure 6

The tables have turned !

- Now we define meter using speed of light and time !
- *The metre is the length of the path travelled by light in vacuum during a time interval of 1/(299 792 458) of a second.*

How fast is the fastest ?

The microwave as a electromagnetic wave generator



How fast is the fastest ?

1. What moves the fastest ?
2. How to measure such a large speed ?
3. Why is there even a single “the fastest” speed ?
4. Modern (20th-century) measurements of the speed
5. How to measure this speed at home