Module 7: The Nature of Light

7.1: Electromagnetic spectrum

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Contents

Cover photo credit: Eielson Air Force Base, Alaska - The Aurora Borealis, or Northern Lights, shines above Bear Lake. By United States Air Force photo by Senior Airman Joshua Strang. Public domain. `https://commons.wikimedia.org/w/index.php?curid=43521154` A beautiful HD compilation video of aurora seen from the ISS: `https://youtu.be/PBJAR3-UvSQ`

Syllabus content: The Nature of Light

Electromagnetic Spectrum

Inquiry question: What is light?

Students:

- investigate Maxwell's contribution to the classical theory of electromagnetism, including:
  - unification of electricity and magnetism
  - prediction of electromagnetic waves
  - prediction of velocity
- describe the production and propagation of electromagnetic waves and relate these processes qualitatively to the predictions made by Maxwell's electromagnetic theory
- conduct investigations of historical and contemporary methods used to determine the speed of light and its current relationship to the measurement of time and distance
- conduct an investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight or incandescent filaments
- investigate how spectroscopy can be used to provide information about:
  - the identification of elements
- investigate how the spectra of stars can provide information on:
  - surface temperature
  - rotational and translational velocity
  - density
  - chemical composition

Background

Faraday's intuition about the nature of light

Figure 1: Faraday by Thomas Phillips, oil on canvas, 1842. Public Domain. Image url: https://commons.wikimedia.org/wiki/File:M_Faraday_Th_Phillips_oil_1842.jpg

Michael Faraday was gifted with great physical insight. After discovering the law of electromagnetic induction, linking the change in a magnetic field to the production of an electric field, Faraday became increasingly convinced that light was also an electromagnetic phenomena. In 1846 Faraday had to unexpectedly replace another speaker (Charles Wheatstone) for a public lecture, and filling in some time at the end of the lecture, allowed himself to make some "speculations" about the nature of light [1]. Faraday pointed out that Wheatstone's measurements of the speed of propagation of electrical signals was very similar to the measured speed of visible light. Faraday believed that this suggested that light is an electromagnetic phenomena which can be described in terms of lines of force that can pass through empty space.

> The view which I am so bold to put forth considers, therefore, radiation as a kind of species of vibration in the lines of force which are known to connect particles and also masses of matter together. It endeavors to dismiss the aether, but not the vibration. The kind of vibration which, I believe, can alone account for the wonderful, varied, and beautiful phenomena of polarization, is not the same as that which occurs on the surface of disturbed water, or the waves of sound in gases or liquids, for the vibrations in these cases are direct, or to and from the centre of action, whereas the former are lateral. [2]

In this quote Faraday is pointing out that his research on polarisation is consistent with light being a transverse, rather than longitudinal wave. 150 years earlier, the phenomena of polarisation also played an important role in the debate between Newton and Huygen's as to whether light was a particle or a wave.

Maxwell's first paper - On Faraday's lines of force

Figure 2: Engraving of James Clerk Maxwell by G. J. Stodart from a photograph by Fergus of Greenock. Public domain. Image url https://commons.wikimedia.org/wiki/File:James_Clerk_Maxwell.png

James Clerk Maxwell was a talented Scottish physicist who made a very significant contribution to physics in unifying the field of electromagnetism, as well as performing important work in optics and thermodynamics.

Maxwell deeply respected Faraday's work and took his ideas about "lines of force" seriously. His first paper on electromagnetism, "On Faraday's lines of force" [3], was published in 1855. In this paper he expressed what was then known about electricity and magnetism in mathematical form using interdependent differential equations and in terms of electric and magnetic "fields", in order to:

[1]

[2]

[3]

> "...show how, by the strict application of the ideas and methods of Faraday, the connection between the very different orders of phenomena which he has discovered may be clearly placed before the mathematical mind."

Unification of electricity and magnetism

Maxwell's great achievement was to write down, in mathematical form, a set of differential equations that completely described the relationship between electric and magnetic fields and the charges that generate them and experience forces as a result of these fields.

The form that Maxwell wrote his equations in is not the form most commonly used today. After Maxwell's early death from cancer at 48, a small group of physicists, primarily Oliver Heaviside, George FitzGerald and Oliver Lodge, continued to explore many aspects of Maxwell's theory that were, in the words of Oliver Heaviside, 'latent' but not 'patent' in his original paper [4]. Together, they were responsible for eventually recasting his set of 20 equations into the four famous, elegant equations now recognised as "Maxwell's equations"[5].

[4] Hunt, B. (1994). The Maxwellians. https://muse.jhu.edu/book/68388

[5]
$$\oint \vec{E}.d\vec{A} = \frac{q_{enc}}{\epsilon_0} \tag{1}$$
$$\oint \vec{B}.d\vec{A} = 0 \tag{2}$$
$$\oint \vec{E}.\vec{ds} = -\frac{d\Phi_B}{dt} \tag{3}$$
$$\oint \vec{B}.\vec{ds} = \mu_0 i + \mu_0\epsilon_0\frac{d\Phi_E}{dt} \tag{4}$$

Maxwell's unification of electricity and magnetism and prediction of EM waves

Maxwell continued to develop his ideas about electromagnetism and 1865 published a groundbreaking paper called "A dynamical theory of the electromagnetic field" [6]. This paper contained a number of very significant achievements:

[6] https://upload.wikimedia.org/wikipedia/commons/1/19/A_Dynamical_Theory_of_the_Electromagnetic_Field.pdf

- "Maxwell's law of induction". Maxwell identified the need for the addition of a term to Ampere's law (which predicts that moving charge produces a magnetic field). This additional term predicts that changing electric fields give rise to magnetic fields, and is the direct electrical analogy of Faraday's law of induction. This additional term is called the "Displacement current", or "Maxwell's law of induction".
- Equations (later expressed as **four** equations) which express the connection between electric and magnetic effects, including Maxwell's "displacement current"
- The demonstration that these equations, taken together, predict the existence of electromagnetic waves.
- The calculation that the speed of these waves is equal (within the experimental uncertainty of the time) to the speed of visible light.

Extension

Displacement current (extension material)

Maxwell pointed out that to make the equations for electromagnetism internally consistent, there must be an effect whereby a changing electric field produces a magnetic field. Consider the situation shown in figure 3. Current is flowing *onto* one plate of a parallel plate capacitor, so increasing the positive charge on that plate, and flowing *off* the other plate, increasing the negative charge on that plate. There is a magnetic field produced by each of the currents in a direction given by the right hand grip rule.
Ampere's law expresses this mathematically as:

$$\oint \vec{B}.\vec{ds} = \mu_0 i$$

where the left hand side of the equation effectively "adds up" the magnetic field around a closed loop, and the right hand side is the current that passes through a surface bounded by that loop (μ_0 is a constant).
If the surface we consider is the circular area of the loop shown on the left, then there is clearly a current passing through this surface, producing a magnetic field. However, we may choose any surface we like, as long as it is bounded by the loop - what if we stretch the surface (like a bubble...) so that it passes through the middle of the plates?
In this case there is no current passing through this new stretched surface, but there is *still* a magnetic field surrounding the wire. This problem can be solved if an additional term was added to Ampere's law, so that

$$\oint \vec{B}.\vec{ds} = \mu_0 i + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

In this case if the surface connecting the closed loop passes through the plates of the capacitor, then while there is no current passing through this surface, there *is* a change in the electric flux through the surface, so that the magnetic field is the same, regardless of where the surface is placed.

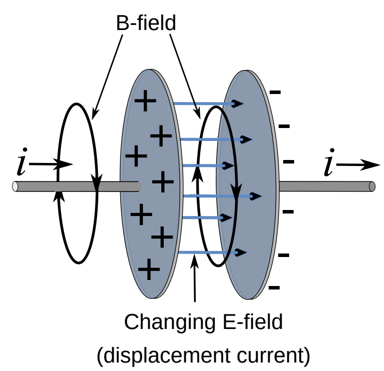


Figure 3: Situation in which a "displacement current" flows. A conventional current flows onto one plate of a parallel plate capacitor, and current flows *from* the other plate. A changing electric field between the plates produces the same magnetic field as the current produces around the wire.

Maxwell's prediction of electromagnetic waves

In his overview of his results in section one of his paper, after outlining the physical meaning of his 20 equations of electromagnetism, Maxwell goes on to say (Part 1, section 20, pg 466):

> "The general equations are next applied to the case of a magnetic disturbance propagated through a non-conducting field, and it is shown that the only disturbances which can be so propagated are those which are transverse to the direction of propagation, and that the velocity of propagation is the velocity v, found from experiments such as those of WEBER, which expressed the number of electrostatic units of electricity which are obtained in one electromagnetic unit.
> The velocity is so nearly that of light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws... ...The conception of the propagation of transverse magnetic disturbances to the exclusion of normal ones is distinctly set forth by Professor Faraday in his "Thoughts on Ray Vibrations". The electromagnetic theory of light, as proposed by him, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation."

In the final section of his paper Maxwell derives the speed of electromagnetic radiation to be (expressed in modern notation):

$$v = \frac{1}{\sqrt{\mu_0 \epsilon_0}}$$

where the constants are μ_0 is the permeability of free space and ϵ_0 is the permittivity of free space. From the values obtained from experimental determination of these constants in Maxwell's time, he calculates this speed to be:

> By the electromagnetic experiments of MM. WEBER and KOHLRAUSCH
>
> $$v = 310,740,000\text{ms}^{-1}$$
>
> and this, according to our result, should be equal to the velocity of light in air or vacuum.

Maxwell then gives the best measurements of the speed of light known at that time:

> The velocity of light in air, by M. FIZEAU's experiments, is
>
> $$V = 314,858,000\text{ms}^{-1}$$
>
> according to the more accurate experiments of M. FOUCAULT
>
> $$V = 298,000,000\text{ms}^{-1}$$
>
> The velocity of light in the space surrounding the earth, deduced from the coefficient of aberration and the received value of the radius of the earth's orbit is
>
> $$V = 308,000,000\text{ms}^{-1}$$

> Hence the velocity of light deduced from experiment agrees sufficiently well with the value of v deduced from the only set of experiments we as yet possess. The value of v was determined by measuring the electromotive force with which a condenser of known capacity was charged, and then discharging the condenser through a galavanometer, so as to measure the the quantity of of electricity in it in electromagnetic measure. The only use of light in the experiments was to see the instruments.
> The value of V found by M. Foucault was obtained by determining the angle through which a revolving mirror turned while the light reflected from it went and returned along a measured course. No use whatever was made of electricity or magnetism.
> The agreement of the results seems to show that light and magnetism are affectations of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.

Hertz confirms Maxwell's prediction of electromagnetic radiation

Note: Hertz is not explicitly mentioned in the new syllabus. I have included the following paragraph as background information only.

Heinrich Hertz confirmed this prediction by producing and detecting electromagnetic waves (radio waves) with a wavelength outside of the visible spectrum. To do this he designed an electrical circuit in which electrons oscillated back and forth at the frequency of the radio waves produced. [7].

Figure 4: Heinrich Hertz. Robert Krewaldt [Public domain]. `https://upload.wikimedia.org/wikipedia/commons/1/1e/Wilhelm_Hallwachs.jpg`

[7] A video I created for the previous syllabus, in which a knowledge of Hertz was explicitly required, is available here: `https://www.youtube.com/watch?v=DQXq7dgEDFk`

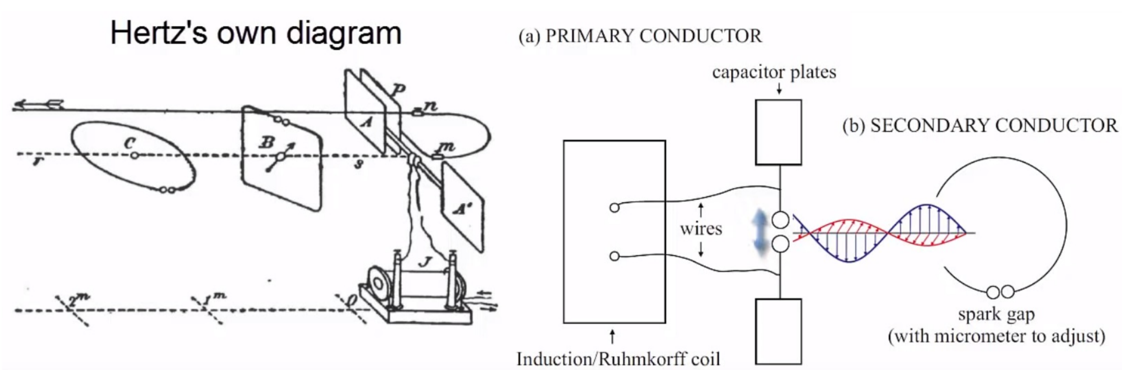


Figure 5: (left) Hertz's own diagram of his experimental setup for producing and detecting radio waves. (Right) A simplified, top-down view diagram.

Production and propagation of electromagnetic waves

Electromagnetic waves are produced by accelerating charges.

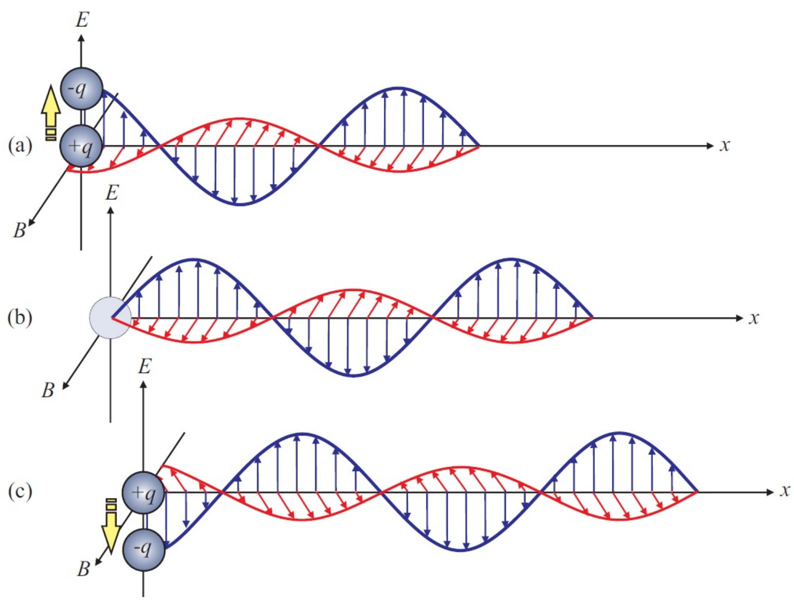


Figure 6: The production of an electromagnetic wave due to an oscillating dipole (i.e. an accelerating charge)

Figure 6 shows a negative charge oscillating around a positive charge located at the origin. As it oscillates up and down it produces an associated electric field (shown in blue) which varies with time in the vertical direction[8].

Maxwell's law of induction predicts that this changing electric field produces a magnetic field (shown in red). As the magnetic field itself also changes with time, this change in B flux induces an electric field, by Faraday's law. This process repeats and the electromagnetic wave propagates continuously through space as a result.

[8] **Activity - Phet simulation of radio waves.** If you can (i.e. if you have a recent version of Java installed...) open the Phet simulation activity on "Radio waves and electromagnetic radiation" `https://phet.colorado.edu/en/simulation/radio-waves` and move the electron up and down - observe what happens to the electric field, as well as the electron in the house.

Summary

In an EM wave, the changing electric and magnetic fields:

- are produced by oscillating (accelerating) charges
- oscillate perpendicular to the direction the EM wave is travelling (are transverse)
- are orientated perpendicular to each other
- oscillate in-phase with each other
- are orientated relative to the electric field in the direction shown in figure 6 [9]

[9] You can remember this pointing your right thumb in the direction that the electromagnetic wave is propagating, then orientate your right hand so your fingers are pointing in the direction of the electric field. If you then bend your fingers 90° they will point in the direction of the magnetic field vector.

Extension

A more detailed explanation - extension

Here we will argue more carefully as to why the magnetic and electric fields must change in the way we have claimed. Consider the small vertical area (in the x-y plane) marked 'P' in figure 7. There is magnetic flux through this region that is increasing with time as the wave moves in the positive x-direction. The electric field vector on the left side of this loop is larger in magnitude that the electric field vector on the right side - so that if we add up the electric field around the perimeter we can use Lenz's law to see there is a net circulation of the electric field in the direction given by Faraday's law of induction.
Similarly, if we consider the horizontal area (in the x-z plane) marked 'Q' in figure 7, we can see that the electric flux through this area is upwards and increasing as the wave moves to the right. Note that Maxwell's induction term in equation 4 is positive, in contrast to Faraday's induction term in equation 3, which is negative. This means that we effectively use the "opposite" of Lenz's law to work out that if the electric flux is increasing in the positive y direction, then this should produce a net circulation of magnetic field in a counter-clockwise direction (seen from above), so the magnetic field vector should be larger on the left of the loop than on the right side, which is consistent with what is shown in figure 7.
The point here is to show that the way that the electromagnetic wave propagates is consistent with both Faraday and Maxwell's laws of induction.

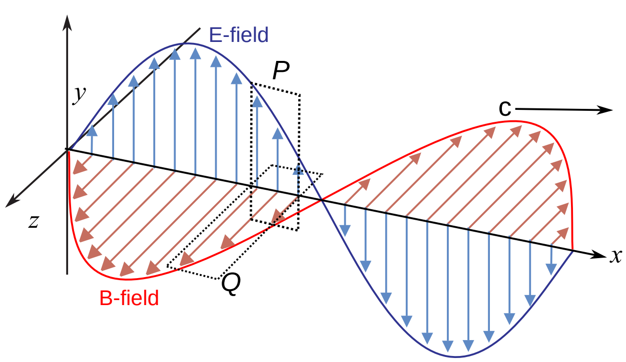


Figure 7: Electromagnetic wave

2019 HSC question on Maxwell and EM radiation

Question 25 (4 marks)

The diagram shows a model of electromagnetic waves. **4**

Relate this model to predictions made by Maxwell.

....

....

....

....

....

....

....

....

An aside: Active learning strategies for material on the history of physics

We are about to cover a section on the syllabus on historical measurements of the speed of light. Throughout Modules 7 and 8 there are substantial sections of the syllabus relating to the history of physics, in particular details about important experiments relating to the nature of light and the nature of matter.

It can be challenging to learn this material as it is in a sense *arbitrary* in a way that most of the physics we have engaged with so far in the course is not - the scientists in question could have performed their experiments otherwise.

In order to learn something new, we need to find a way to connect it to something we already know, as well as to recall regularly it over an extended period of time (spaced retrieval) to gradually encode it in our long term memory.

To facilitate this process in modules 7 and 8, I suggest two strategies.

Strategy 1: Attach the new information to physics you already know

Take notes about the material in a way that specifically ties the experiment to the physics you know - aim to store it associated with that information in your memory.

For example, the experiments we will learn about in the next section generally use one of two methods to measure the speed of a wave:

1. "**Time of flight" measurements**. Scientists time how long light takes to travel a known distance.
2. "$c = f\lambda$**" measurements**. Scientists measure the wavelength of light of a known frequency, and use $c = f\lambda$ to determine the speed of light.

For each experiment we cover, identify which of these approaches is used and how each piece of necessary information is obtained. One experiment uses neither approach (I'll leave you to determine which!).

Strategy 2: Using a "thinking routine" such as "Claim, Evidence, Question"

It is necessary for our brain to actively attend to the material we wish to learn. Utilising a thinking routine such as "Claim, Evidence, Question" is one reasonable approach that could facilitate this.

1. Imagine that a student writing summary notes for this material, and **making a *claim*** such as "*Galileo assumed that light was roughly 10 times the speed of sound*" or "*Galileo and his assistant stood on two hilltops, two miles distant*" (these are claims made by Adam Savage in the Youtube video we will watch on Galileo's experiment in the next section). There are many summaries of the new HSC physics syllabus on the web (or in tutoring notes ;) that you can use as a source of claims you could test. Ultimately you are searching for valid claims that you will use in your own summaries of this material.
2. As we work through the original source material, **test the claim by searching for *evidence*, that supports or refutes the claim**. You should utilise first-hand (original) sources whenever these are available, or well-referenced second hand sources by authors with qualifications in the field (if, for example, the original paper is in German and there is no available translation, or the physics is too complex)
3. Finally, it can be useful (not just in this material, but when learning any new material), to **explicitly identify (write down) *questions***; places where the material is not yet making complete sense. By explicitly identifying your questions, you are priming your brain to actively attend to new information as you seek to resolve these with satisfying answers.

Historical measurements of the speed of light

Galileo - Lanterns on a distant hill (1638)

In his "Two new sciences", published in 1638, [10] Galileo describes an experiment to attempt to measure the speed of light by using two lanterns. We will use this for our discussion of Fizeau's experiment as well. The two observers holding the lanterns are separated by some distance (Galileo says he performed it at a distance of a mile). One observer uncovers their lantern, and when this light is seen by the second observer they uncover their lantern. The first observer attempts to measure any difference between the time between uncovering their own lantern and seeing the light from the second lantern compared to performing the same experiment when they are close together.

Galileo was unable to detect any difference in the time taken in the two cases, so concludes that light if light does not travel instantaneously, then it at least travels extremely rapidly.

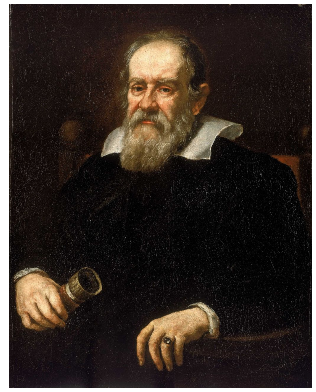


Figure 8: Galileo Galilei, Justus Sustermans 1636 [Public domain].

[10] Online english translations: `http://galileoandeinstein.physics.virginia.edu/tns_draft/index.html` or `http://files.libertyfund.org/files/753/Galileo_0416_EBk_v6.0.pdf`

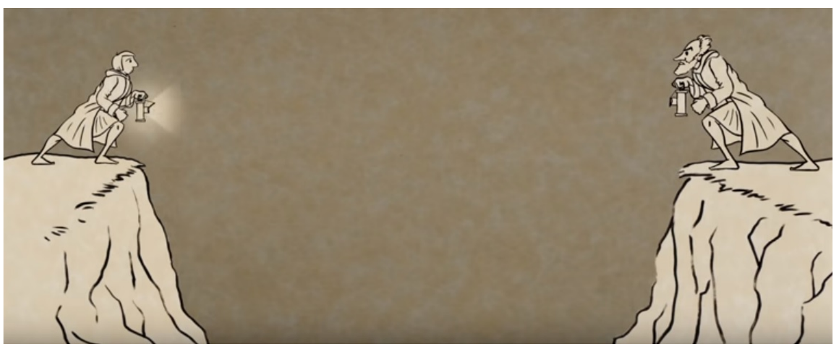


Figure 9: Still of an animation of Galileo's attempt to measure the speed of light using two observers with lanterns from Adam Savage's TED-Ed talk, `https://www.youtube.com/watch?v=F8UFGu2M2gM`, 4min in.

Except from Galileo's "Two new sciences", page 49:

> SAGR.
> But of what kind and how great must we consider this speed of light to be? Is it instantaneous or momentary or does it like other motions require time? Can we not decide this by experiment?
> SIMP.
> Everyday experience shows that the propagation of light is instantaneous; for when we see a piece of artillery fired, at great distance, the flash reaches our eyes without lapse of time; but the sound reaches the ear only after a noticeable interval.
> SAGR.
> Well, Simplicio, the only thing I am able to infer from this familiar bit of experience is that sound, in reaching our ear, travels more slowly than light; it does not inform me whether the coming of the light is instantaneous or whether, although extremely rapid, it still occupies time. An observation of this kind tells us nothing more than one in

which it is claimed that "As soon as the sun reaches the horizon its light reaches our eyes"; but who will assure me that these rays had not reached this limit earlier than they reached our vision?
SALV.
The small conclusiveness of these and other similar observations once led me to devise a method by which one might accurately ascertain whether illumination, i. e., the propagation of light, is really instantaneous. The fact that the speed of [88] sound is as high as it is, assures us that the motion of light cannot fail to be extraordinarily swift. The experiment which I devised was as follows:
Let each of two persons take a light contained in a lantern, or other receptacle, such that by the interposition of the hand, the one can shut off or admit the light to the vision of the other. Next let them stand opposite each other at a distance of a few cubits and practice until they acquire such skill in uncovering and occulting their lights that the instant one sees the light of his companion he will uncover his own. After a few trials the response will be so prompt that without sensible error [svario] the uncovering of one light is immediately followed by the uncovering of the other, so that as soon as one exposes his light he will instantly see that of the other. Having acquired skill at this short distance let the two experimenters, equipped as before, take up positions separated by a distance of two or three miles and let them perform the same experiment at night, noting carefully whether the exposures and occultations occur in the same manner as at short distances; if they do, we may safely conclude that the propagation of light is instantaneous; but if time is required at a distance of three miles which, considering the going of one light and the coming of the other, really amounts to six, then the delay ought to be easily observable. If the experiment is to be made at still greater distances, say eight or ten miles, telescopes may be employed, each observer adjusting one for himself at the place where he is to make the experiment at night; then although the lights are not large and are therefore invisible to the naked eye at so great a distance, they can readily be covered and uncovered since by aid of the telescopes, once adjusted and fixed, they will become easily visible.
SAGR.
This experiment strikes me as a clever and reliable invention. But tell us what you conclude from the results.
SALV.
In fact I have tried the experiment only at a short distance, less than a mile, from which I have not been able to ascertain with certainty whether the appearance of the opposite light was instantaneous or not; but if not instantaneous it is extraordinarily rapid - I should call it momentary; and for the present I should compare it to motion which we see in the lightning flash between clouds eight or ten miles distant from us. We see the beginning of this light - I might say its head and[89] source - located at a particular place among the clouds; but it immediately spreads to the surrounding ones, which seems to be an argument that at least some time is required for propagation; for if the illumination were instantaneous and not gradual, we should not be able to distinguish its origin - its center, so to speak - from its outlying portions.

Your notes on Galileo's measurement of the speed of light

Did Galileo use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

Did you find evidence in Galieo's description of his experiment to support the two claims made by Adam Savage in the YouTube video?

"*Galileo assumed that light was roughly 10 times the speed of sound*" and

"*Galileo and his assistant stood on two hilltops, two miles distant*"

Are these valid claims or do one or other or both need to be amended?

Is there a question you have about Galileo's determination of the speed of light?

Ole Rømer - Delays in the eclipse of Io by Jupiter (1676)

Ole Rømer was a Danish astronomer working at the Paris Observatory making systematic observations of Jupiter's closest moon Io [11,12]. This moon is eclipsed (i.e. passes behind) Jupiter at regular intervals governed by its orbital period. Rømer noticed that, over several months, the time at which Io was eclipsed by Jupiter became later and later than would be expected, then gradually earlier again.

He correct surmised that this was due to the distance between earth and Jupiter changing as Earth orbited the sun. It takes the light from the eclispe event some time to reach earth from Jupiter, so if earth is travelling further away from Jupiter as measurements are taken, then the eclipse appears to occur later than expected (i.e. the period is longer than average). If earth is travelling towards Jupiter, then the eclipse appears earlier (i.e. the period for the rotation appears shorter than average). On the basis of these measurements, Rømer calculated that it took light 22min to traverse the diameter of earth's orbit around the sun.

Original source material:

- Rømer's original paper ("A demonstration concerning the motion of light, communicated from Paris, in the Journal des Scavans, and here made English", Philosophical Transactions of the Royal Society of London, 12 (136): 893âĂŞ94, 1677. JSTOR 101779. See pg. 733 for the diagram referred to in the text.`https://archive.org/details/philosophicaltra02royarich/page/397/mode/1up?view=theater`.
- A paper by Albert Helden from Rice University also discusses Rømer's measurement in detail, noting that the value for the speed of light obtained by Rømer's measurement depends upon the value assumed for the radius of the earth's orbit: (`https://adsabs.harvard.edu/full/1983JHA....14..137V`).

Figure 10: Ole Rømer c. 1700. Image credit: By Jacob Coning - Frederiksborg Museum, Public Domain, `https://commons.wikimedia.org/w/index.php?curid=11617410`

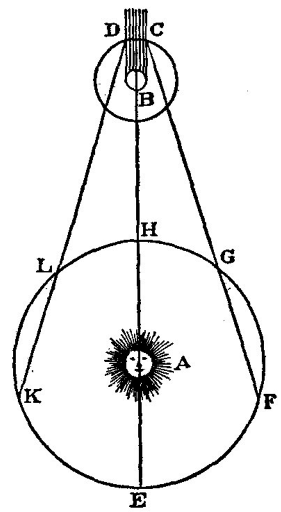


Fig. 70.

Figure 11: Illustration from Ole Rømer's 1676 article showing lines of sight from the earth in different parts of its orbit around the sun to the eclipse of Io as it orbits Jupiter. Between D and C Io is behind Jupiter. The light from the moment at which Io is eclipsed takes longer to reach earth when the earth is on the opposite side of the sun to Jupiter, so appears to occur *later* than expected.

[11]

[12] `https://archive.org/details/philosophicaltra02royarich/page/397/mode/1up?view=theater`. I also used the *excellent* lecture notes of Michael Fowler of the University of Virginia for this section `http://galileo.phys.virginia.edu/classes/109.mf1i.fall03/lectures09.pdf` and the paper by Albert van Helden `http://adsabs.harvard.edu/full/1983JHA....14..137V`

Notes on Rømer

Did Rømer use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

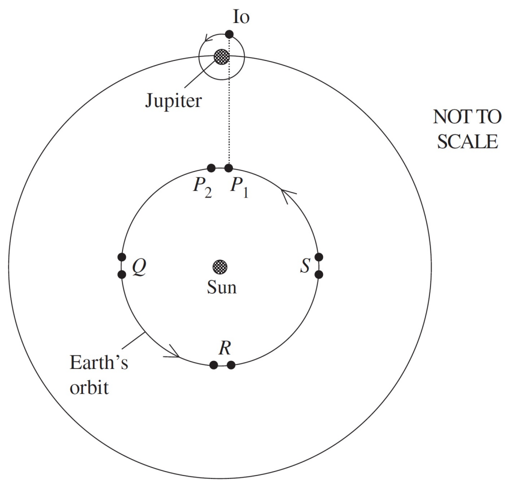
Identify a claim you about Rømer's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Rømer's determination of the speed of light?

Past HSC question on Rømer

18 An observer sees Io complete one orbit of Jupiter as Earth moves from P_1 to P_2, and records the observed orbital period as t_P. Similarly, the time for one orbit of Io around Jupiter was measured as Earth moved between the pairs of points at Q, R and S, with the corresponding measured periods of Io being t_Q, t_R and t_S.



Which measurement of the orbital period would be the longest?

A. t_P

B. t_Q

C. t_R

D. t_S

Figure 12: Question 18 from the 2020 HSC

James Bradley - The aberration of starlight (1728)

In 1725 James Bradley was attempting to measure stellar parallax - the apparent movement of the position of near stars relative to distant stars due to the change in *position* of the earth as it moves around the sun, and so determine the distance to the close stars [13]. He succeeded in measuring a change in position of the star Gamma Draconis of approximately 40 seconds of arc over the course of a year, however the maximum and minimum values of the motion occurred a quarter of a cycle out of phase from where they would be expected to occur if the effect was due to stellar parallax.

Bradley eventually surmised that the effect was due to the variation in the *velocity* of earth relative to the direction light was arriving from the star, not the *position* of the earth in its orbit (as would be the case for parallax).

"I perceived that, if light was propagated in time, the apparent place of a

13

Figure 13: James Bradley. By Thomas Hudson c. 1745 [Public domain]

fixt Object would not be the same when the eye was at rest, as when it was moving in any other direction, than that of the line passing between through the eye and the object; and that, when the eye is moving in different directions, the apparent place of the object would be different." (`https://royalsocietypublishing.org/doi/pdf/10.1098/rstl.1727.0064` See page 646)

When the earth was moving with a component of its velocity perpendicular to the direction light was arriving from the star, this velocity appears to be added (via vector addition) to the velocity of the light from the star and so the *angle* at which the light appears to be arriving changes, and thus the apparent position of the star in the sky changes.

As an analogy, consider standing in vertically falling rain, then consider walking or running through the same rain. The angle at which the rain arrives changes in your reference frame, so in your new reference frame each raindrop now appears to originate from a position in the sky just to the front of you, wheras in the stationary frame it appeared to originate from directly above you. [14]
From the magnitude of the apparent motion observed, and knowing the orbital velocity of the earth around the sun, Bradley determined the speed of light to be 301000kms^{-1}.
As a class we will have a look at the stellar Abberation simulation by Todd Timberlake: `https://www.compadre.org/osp/items/detail.cfm?ID=12029`

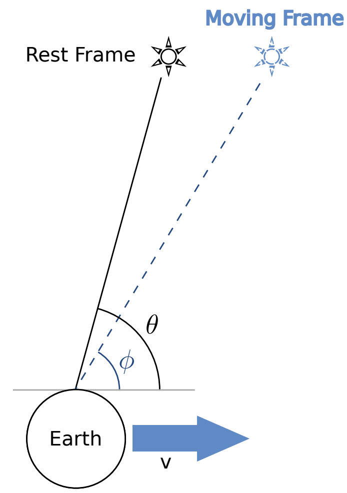


Figure 14: Abberation of starlight due to the motion of the earth.
As the earth moves in its orbit around the sun it is sometimes moving with a component of its velocity perpendicular to the direction light is arriving from the star. This velocity is added as a vector to the velocity of the light to give the apparent direction of the source of the light in the earth's reference frame. Image credit: Ahalda at English Wikipedia [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]

[14] The NASA site is also useful, not only discussing stellar abberation, but also applications/effect of abberation in other areas: `https://www-spof.gsfc.nasa.gov/stargaze/Saberr.htm`

Notes on Bradley's use of stellar aberration to measure the speed of light

Did Bradley use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Bradley's measurement of the speed of light you could test using the original source material:

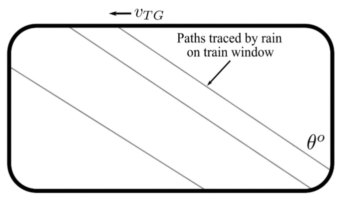
Evidence to support or refute the claim:

Is there a question you have about Bradley's measurement?

Past Ruse Trial question on Bradley

Question 31 (3 Marks)

A student standing in the rain on a windless day measures the velocity of raindrops to be v_{RG} directly downwards. Another student travelling on a train moving with a velocity of v_{TG} to the left relative to the ground observes that the apparent direction that the rain is arriving from is θ° to the vertical.



a) Construct an equation which relates v_{TG}, v_{RG} and the angle θ°. **1**

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A similar effect is observed when light arriving from stars is observed from the Earth. The apparent direction of the starlight (that is, the apparent position of the star) changes as the direction of the Earth's motion around the sun changes over a year (Figure 1). The largest shift in position, of $0^o 0' \, 20.5"$, occurs for stars near the poles (Figure 2).

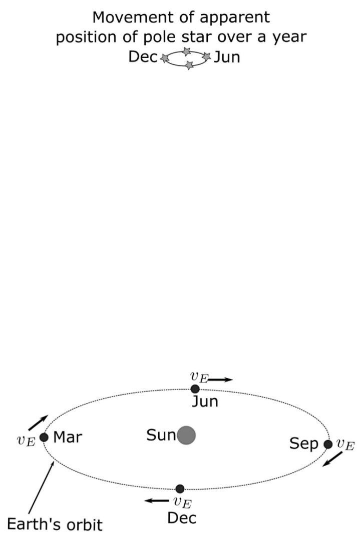

Figure 1

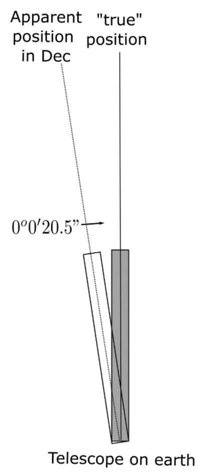

Figure 2

(b) Showing all working, determine the speed of light from the information above if the distance from the Earth to the Sun is known to be $r_E = 1.5 \times 10^{11}$m, and its orbital period around the sun is $T = 365.25$ days. **2**

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Fizeau - Toothed wheel (1849)

Hippolyte Fizeau and Léon Foucault were originally collaborators who worked together on a number of scientific endevours, such as improving the photographic process, but later became competitors to measure the speed of light using terrestrial means (Fizeau was the first) and to decide between the particle and wave model of light by comparing the speed of light in water to that in air (Foucault was first). Fizeau's apparatus is shown in figure 16[15] and consisted of a light source which was focused and then the beam passed through a rotating toothed wheel. The beam travelled to a distant mirror and then returned through the toothed wheel to an observer. Fizeau adjusted the speed of rotation until it was fast enough that in the time taken for the beam to travel to the mirror and back, the wheel had rotated so that the next tooth blocked the beam. Knowing the angular speed of the wheel and the distance the light had traveled, Fizeau could calculate the speed of light, obtaining a value of $3.13 \times 10^8 \mathrm{ms}^{-1}$, which is within 4% of the true value.
Original source: H. Fizeau, Comp. Rend. Acad. Sci. (Paris) 29 (1849), 90-92 (original pages in French: `https://docs.google.com/document/d/1-VJZICPD6LrHjWfHEzgZ8r3xcTl8iQkSshIPSNrR7ns/edit?usp=sharing`, pg. 2) [16].

Figure 15: Fizeau. Eugène Pirou (1841-1909) [Public domain], via Wikimedia Commons

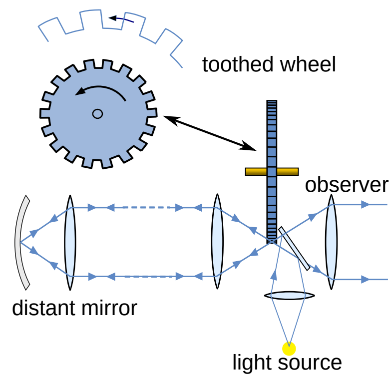


Figure 16: Fizeau's experiment to measure the speed of light. Image credit: Adapted from `http://www.schoolphysics.co.uk/age16-19/Wave%20properties/Wave%20properties/text/Speed_of%20light/index.html` Keith Gibbs (2016).

[15] See Adam Savage's Ted-Ed talk for a good animation as well, 4min in: `https://www.youtube.com/watch?v=F8UFGu2M2gM`

[16] Link to .pdfs of pages of Fizeau's original paper and a (babelfish!) English translation `https://skullsinthestars.com/2008/03/31/fizeaus-experiment-the-original-paper/`

Notes on Fizeau's measurement of the speed of light

Did Fizeau use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Fizeau's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

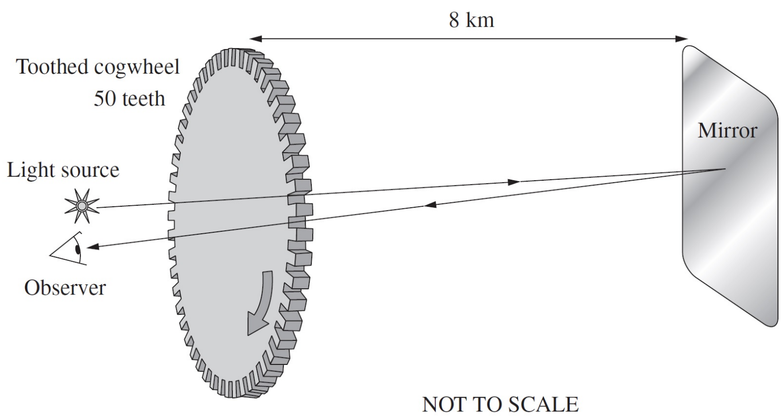
Is there a question you have about Fizeau's measurement?

Question on Fizeau's measurement of the speed of light

5 Figure 17: Question on Fizeau from the "Additional sample questions" for the new HSC syllabus

In the 1840s, French physicist, Hippolyte Fizeau performed an experiment to measure the speed of light. He shone an intense light source at a mirror 8 km away and broke up the light beam with a rotating cogwheel. He adjusted the speed of rotation of the wheel until the reflected light beam could no longer be seen returning through the gaps in the cogwheel.

The diagram shows a similar experiment. The cogwheel has 50 teeth and 50 gaps of the same width.



Explain why specific speeds of rotation of the cogwheel will completely block the returning light. Support your answer with calculations.

Léon Foucault - Rotating mirror (1862)

Foucault also conducted a measurement of the speed of light, but using a somewhat different approach. Instead of using a toothed wheel, he used a rotating mirror. The idea is that light hitting the rotating mirror produced a reflected beam that swept around in the arc of a circle. When the rotating beam was at a certain position this beam would hit a distant mirror and be reflected back (at all other positions the reflected beam simply missed the distant mirror). In the time for light to travel from the rotating mirror to the distant mirror and back again, the rotating mirror would have turned slightly, so that the beam reflected back towards the source of light would be reflected at a different angle, and so arrive at a position offset from the original beam. The amount of deflection could be measured, related to the time taken for the mirror to rotate that amount, and so to the time taken for light to traverse the known distance to the far away mirror could be calculated.
Foucault was primarily focused on determining whether the speed of light in water was greater or less than that of air (for the purposes of deciding between the wave and particle models of light) his 1853 thesis [17] does not give an absolute measurement of the speed of light in air. However, in 1962 Foucault did obtain an absolute measurement of the speed of light of $280 \times 10^6 \mathrm{ms}^{-1}$ which is within 1 percent of the correct value[18].

Figure 18: Léon Foucault, [Public domain], via Wikimedia Commons.

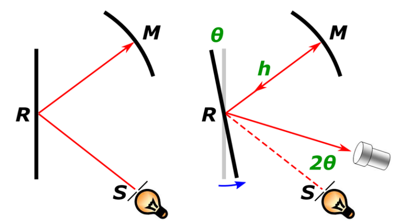


Figure 19: Foucault's experiment. The beam from a source S hits a rotating mirror. When the mirror is in a certain precise position, the beam hits a distant mirror which reflects it back to the rotating mirror. In the time it takes light to do this trip, the mirror has rotated slightly more, causing the beam reflected from it to be offset from the source beam. The amount of offset allows a determination of the time taken for light to travel to the distant mirror and back, and so a measurement of the velocity of light.

Notes on Foucault's measurement of the speed of light

Did Foucault use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Foucault's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Foucault's measurement?

[17] A .pdf of the in French is available here: `http://jubilotheque.upmc.fr/fonds-theses/TH_000075_001/document.pdf?name=TH_000075_001_pdf.pdf`

[18] An excerpt from "Toothed wheels and rotating mirrors: Parisian astronomy and mid-nineteenth century experimental measurements of the speed of light" by William Tobin, Vistas in Astronomy, Vol. 36 (1993) pg 253-294. (`https://www.sciencedirect.com/science/article/abs/pii/0083665693901324`) is provided on page 6 at: `https://docs.google.com/document/d/1-VJZICPD6LrHjWfHEzgZ8r3xcTl8iQkSshIPSNrR7ns/edit?usp=sharing`

Question on Foucault's measurement of the speed of light

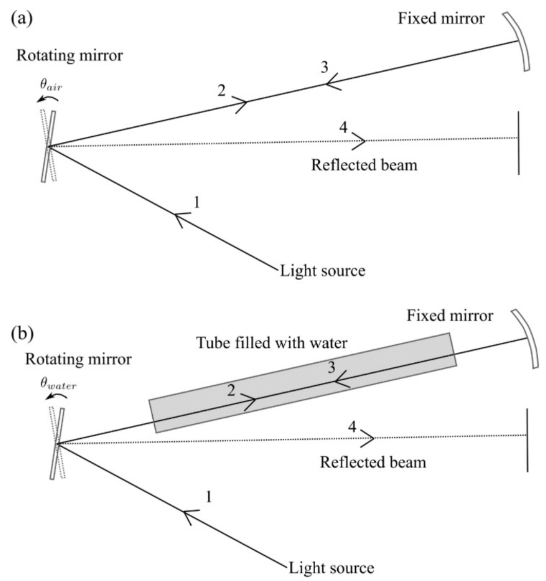
While we will need to wait until we deal with Newton and Huygen's models of light to answer this question fully, it is worthwhile to do the first part now to allow us to actively engage with how Foucault's measurement works.

An experiment was conducted to test the predictions of Newton and Huygens' models of light.

In the experiment a rotating mirror was used to deflect light along the sequence of paths 1 to 4 in the diagram.

In one part of the experiment, shown in (a), light moved through **air** along paths 2 and 3, and the angle through which the rotating mirror turned in this time was measured to be θ_{air}.

In another part of the experiment, shown in (b), light moved through **water** along paths 2 and 3, and the angle through which the rotating mirror turned in this time was measured to be θ_{water}.



Which angle would be the largest, and which model of light is supported by this result?

	Larger angle of rotation	Model of light supported by results
A.	θ_{air}	Huygens
B.	θ_{air}	Newton
C.	θ_{water}	Huygens
D.	θ_{water}	Newton

Figure 20: A multiple choice question relating to Foucault's comparison of the speed of light in water and in air

Albert Michelson - Higher precision using Foucault's technique (1879, 1927 and 1935)

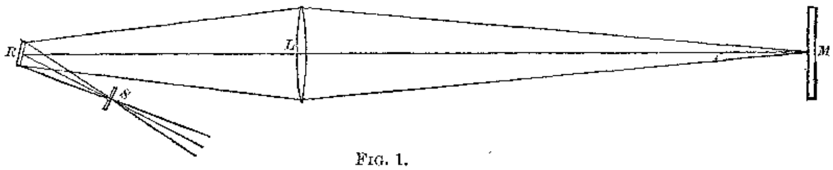


Fig. 1.

Figure 21: A simplified top-down diagram of Michelson's experimental setup taken from his 1879 paper. R is the rotating mirror and M the distant mirror. S is the slit through which light from the source passes. L is the lens which forms the image of the slit on the distant mirror.

Albert Michelson was an instructor in physics and chemistry at the Naval Academy at Annapolis, Maryland in the U.S. in 1879. He had been given the task of repeating Foucault's measurement of the speed of light as a lecture demonstration. He realised that with higher precision optics so that he could greatly increase the distance to the distant mirror, he could repeat the experiment with a higher level of precision [19]. A schematic of Michelson's experimental setup (leaving out all the complex equipment required to measure the deflection, spin the prism at high speed and measure the rate of rotation!) is shown in figure 21. Using a distance of 2000ft to the distant mirror, and significantly improved optics for lens and mirror, Michelson obtained a value for the speed of light of $(299940 \pm 50\text{kms}^{-1})$, which is within 0.05% of the currently accepted value.[20]

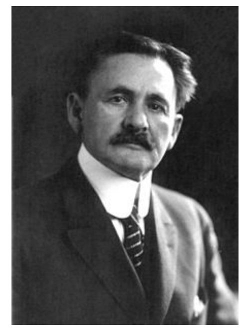


Figure 22: Albert Michelson. [Public domain], via Wikimedia Commons

[19]

[20] Fulltext of 1879 paper.

[21] Fulltext of 1927 paper

In 1927 Michelson completed another, more precise, measurement [21] using an octagonal prism (made of glass or steel) instead of a flat mirror to produce a brighter image and allow a longer baseline between Mt. Wilson and Mt. San Antonio in California. The value obtained from this experiment was $299796 \pm 4\text{kms}^{-1}$, which is within 0.001% of the currently accepted value.

Michelson began a further experiment inside an evacuated steel tube about a mile long [22], but passed away part way through the experiment. The experiment was completed by Pease and Pearson, with a result of $(299774 \pm 11\text{kms}^{-1})$.

[22] Fulltext of 1935 paper

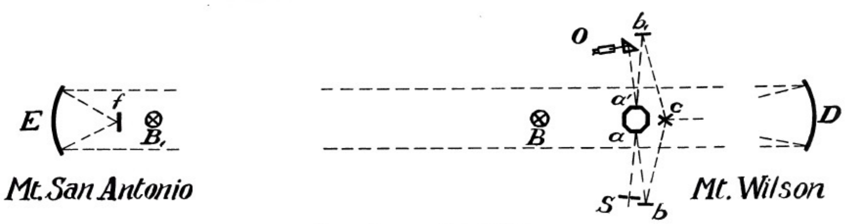


Fig. 1.—Arrangement of apparatus

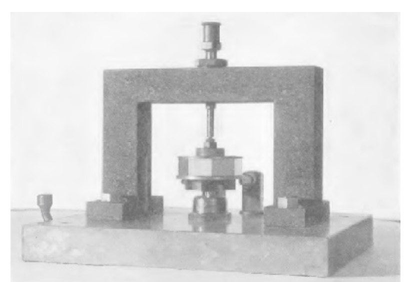


Figure 23: Diagram of Michelson's 1927 experiment, and his rotating octagonal glass prism, from his paper.

Notes on Michelson's measurement of the speed of light

Did Michelson use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how he obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Michelson's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Michelson's measurement?

Karolus and Mittelstadt - Kerr cell (1928)

In 1928 Karolus and Mittelstadt used a "Kerr cell" in a setup conceptually similar to Fizeau's toothed wheel. This device uses a material (for example, nitrobenzene) which can very rapidly change its optical properties in response to a voltage, so effectively switching a beam of light on and off. The increase in switching frequency translates to a more precise measurement of time, and meant that they could use a greatly reduced baseline distance.

Original source material:
Karolous and Mittelstadt published in German, however a contemporary description of their work is provided in a review of measurements of the speed of light by M. E. J. Gheury de Bray in 1936 (who give their measurement as $(299778 \pm 20) \times 10^3 \mathrm{ms}^{-1}$). Other discussions of their work are provided in a review of Kerr cells by J.W. Beams (`http://www.phys.virginia.edu/History/Beams/Papers/Beams%201930f.pdf` pg. 791).

> Quite recently, an ingenious modification of the former method has been used by KAROLUS and MITTELSTAEDT : instead of a toothed wheel, a Kerr cell, at the terminals of which was applied an alternating difference of potential, was used to interrupt periodically the passage of a luminous beam the path of which passed through the transparent liquid dielectric of the cell, between the plates of the condenser (***Physikalische Zeitschrift***, 1928, pp. 698-702; 1929, pp. 165-167). The chief advantage of this method is that the frequency of the periodic interruption of the beam can be accurately calculated, which was not the case when the toothed wheel was used; moreover, a much higher frequency can be used with this method, of the order of a million per second, so that a correspondingly short base (in this case 41.386 metres) can be used while maintaining as high a standard of accuracy as was obtained over long bases with ordinary frequencies.

Figure 24: Description of Karolus and Mittelstadt's measurement of the speed of light by Gheury de Bray. (`https://www.jstor.org/stable/225381`)

Notes on Karolus and Mittelstadt's measurement of the speed of light

Did Karolus and Mittelstadt use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how they obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Karolus and Mittelstadt's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Karolus and Mittelstadt's measurement?

No.	Average date.	Investigator	Method.	Length of base.	Base.	Velocity, km./sec.	Medium	Remarks.
1	1849.5	Fizeau	TW	8,633 m.	Suresnes—Montmartre	315,300	Air	
2	1862.8	Foucault	RM	20 m.	Paris Observatory	298,000 ± 500	,,	
3	1872.0	Cornu (*a*)	TW	10,310 m.	École Polytechnique—Mont Valérien	298,500 ± 300	,,	Preliminary value (rejected as doubtful).
4	1874.8	,, (*b*)	,,	22,910 m.	Paris Observatory—Montlhéry	**300,400 ± 300**	Vac.	
5	,,	Cornu-Helmert	,,	,,	,,	**299,990 ± 200**	,,	Cornu's results discussed by Helmert.
6	1878.0	Michelson (*a*)	RM	1,986.23 ft.	U.S. Naval Academy	300,140 ± 300	,,	Preliminary value (discarded).
7	1879.5	,, (*b*)	,,	,,	,,	**299,910 ± 50**	,,	Corrected value.
8	1880.9	Newcomb (*a*)	,,	2,550.9 m.	Fort Meyer—U.S. Naval Observatory	299,627	Air	Doubtful.
9	1881.0	Young and Forbes	TW	18,212.2 ft. and 16,835.0 ft.	Wemyss Bay—Hills behind Innellan	301,382	Vac.	Admittedly unreliable.
10	1881.7	Newcomb (*b*)	RM	3,721.2 m.	Fort Meyer—Washington Monument	299,694	Air	Doubtful.
11	1881.8	,, (*c*)	,,	—	—	299,810	Vac.	Mean of (*a*), (*b*), and (*d*).
12	1882.7	,, (*d*)	,,	3,721.2 m.	Fort Meyer—Washington Monument	**299,860 ± 30**	,,	Final declared value.
13	1882.8	Michelson (*c*)	,,	2,049.532 ft.	Case School of Applied Science, Cleveland	**299,853 ± 60**	,,	
14	1900.4	Perrotin (*a*)	TW	11,862.2 m.	Nice Observatory—La Gaude	299,900 ± 80	Vac.	Preliminary discussion (superseded).
15	1900.4	,, (*b*)	,,	,,	,,	300,032 ± 215	,,	Final discussion (discarded).
16	1901.4	,, (*c*)	,,	—	—	299,880 ± 50	,,	Mean of (*a*) and (*d*) (superseded).
17	1902.4	,, (*d*)	,,	45,950.7 m.	Nice Observatory—Mont Vinaigre	299,860 ± 80	,,	Preliminary discussion (superseded).
18	1902.4	,, (*e*)	,,	,,	,,	**299,901 ± 84**	,,	Perrotin's final declared value.
19	1924.6	Michelson (*d*)	RM	35,385.53 m.	Mt. Wilson Observatory—Mt. St. Antonio	**299,802 ± 30**	,,	Preliminary (corrected) value.
20	1926.0	,, (*e*)	,,	,,	,,	**299,796 ± 4**	,,	
21	1928.5	Karolus and Mittelstaedt	Kerr Cell	41,386 m.	Leipzig	**299,778 ± 20**	,,	Frequency of the order of a million.
22	1932.1	Pease and Pearson	RM	1 mile	Mt. Wilson Observatory	**299,774 ± 10**	,,	In a pipe line.

Figure 25: Table of historical measurements of the speed of light. From `https://www.jstor.org/stable/225381`, page 439.

Contemporary measurements of the speed of light

Essen - Cavity resonator (1950)

In 1950 Essen [23] used a cylinder 6.5cm in diameter and of a variable length as a cavity resonator for microwaves. The length of the cavity was adjusted to produce a sequence of resonances for microwaves of known frequency. Knowing the length at which resonances occur the corresponding wavelengths, and so the speed could be determined to be c = $(299792.5 \pm 3)\text{kms}^{-1}$ (the speed of sound is commonly measured in an analogous manner).

[23] `https://royalsocietypublishing.org/doi/abs/10.1098/rspa.1950.0172`

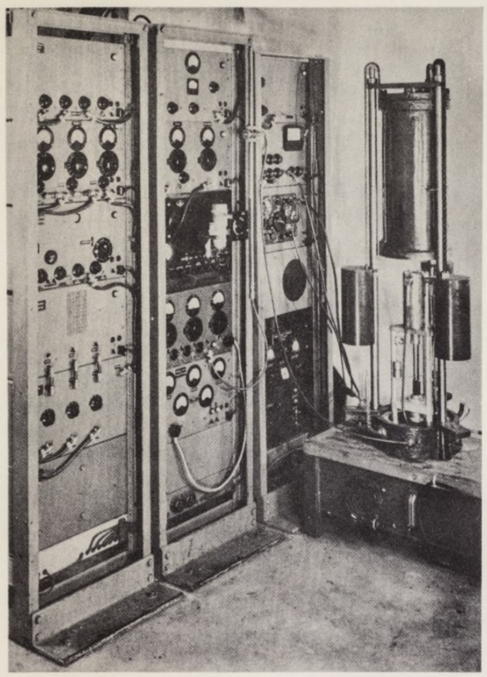


FIGURE 3. Cavity resonator and micro-wave frequency standard. The resonator is on the right, together with the cover which can be lowered and evacuated. The resonator is excited by a harmonic of a quartz-controlled oscillation multiplied up to the appropriate frequency in the equipment on the left, which also contains the receiver used for detecting the resonance.

Figure 26: A photograph of Essen's microwave cavity resonator.

Notes on Essen's measurement of the speed of light

Did Essen use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how they obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Essen's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Essen's measurement?

Froome - Microwave interferometer (1958)

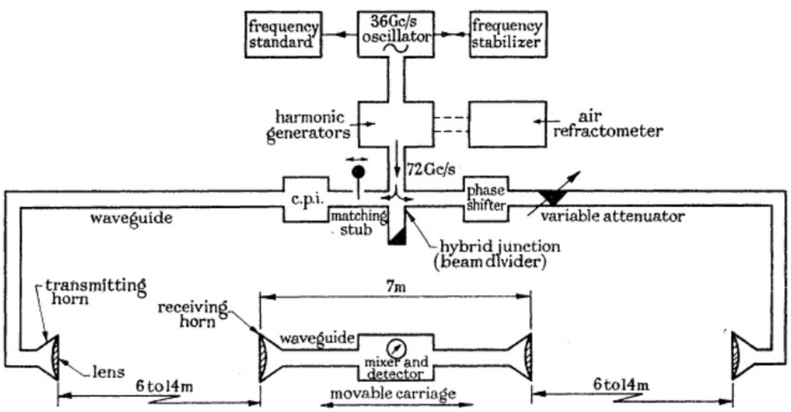


FIGURE 1. Diagram of 72 Gc/s interferometer.

Figure 27: Froome's microwave interferometer.

Froome used a microwave interferometer[24] - a device which splits a beam and then recombines the beam to produce an interference pattern. As the distance travelled by the two parts of the beam is changed the beams move in and out of phase, over a distance equal to a whole wavelength, allowing a measurement of the wavelength and so the speed, of waves of a known frequency. Froome obtained a result of $(299792.50 \pm 0.10)\mathrm{kms}^{-1}$.

[24] `https://www.jstor.org/stable/100591?read-now=1&seq=1#page_scan_tab_contents` The fulltext available with a JSTOR account.

Evenson et. al - Laser interferometer (1972)

In 1972 a group of researchers from the National Bureau of Standards in Boulder, Colorado, independently measured the wavelength and frequency of laser light from a methane laser against primary standards, finding the speed by multiplying these values to be $(299792456.2 \pm 1.1)\mathrm{ms}^{-1}$, which was 100 times more precise than previous measurements[25]. The precision of the measurement was limited by the asymmetry of the Kr spectral line used to define the meter at that time.

[25] See https://tf.nist.gov/general/pdf/307.pdf page 358

Notes on Froome or Evenson's measurement of the speed of light

Did Froome or Evenson use a "time of flight" or a "$c = f\lambda$" approach to measure the speed of light? (or neither?)

Identify how they obtained the pieces of information required to use this approach to measure the speed of light:

Identify a claim you about Froome or Evenson's measurement of the speed of light you could test using the original source material:

Evidence to support or refute the claim:

Is there a question you have about Froome or Evenson's measurement?

Table 6.1. Speed of light measurements since 1958

Year	Author	Ref.	Method	c [km/s]	δc [km/s]
1958	Froome	[6.13]	Radio interferometer	299792.5	0.1
1961	Cutkosky and Thomas	[6.48]	Ratio of units	299791.96	0.8
1965	Kolibayev	[6.49]	Electro-optical	299792.6	0.06
1965	Rank et al.	[6.50]	Spectroscopic	299792.8	0.4
1966	Karolus	[6.51]	Electro-optical	299792.44	0.2
1967	Grosse	[6.52]	Electro-optical	299792.5	0.05
1967	Simkin et al.	[6.53]	Radio interferometer	299792.56	0.11
1971	Bjerhammar	[6.54]	Electro-optical	299792.375	0.060
1972	Bay et al.	[6.11]	He–Ne $\lambda\nu$ (0.633 μm)	299792.462	0.018
1972	Baird et al.	[6.47]	CO_2 $\lambda\nu$ (9 and 10 μm, avg.)	299792.460	0.006
1972	Evenson et al.	[6.12]	He–Ne $\lambda\nu$ (3.39 μm) c.g.	299792.4562	0.0011
			peak	299792.4587	0.0011
1973	Guelachvili	[6.55]	Spectroscopic	299792.46	0.07
1973	Baird and Blaney et al.	[6.47, 46]	CO_2 $\lambda\nu$ (9.32 μm)	299792.457	0.006
1973	CCDM	[6.6, 10]	He–Ne $\lambda\nu$ (3.39 μm)	299792.458	0.0012

Figure 28: Table of contemporary measurements of the speed of light. From https://tf.nist.gov/general/pdf/307.pdf, page 363.

Defining length in terms of the speed of light

The 15th General Conference on Weights and Measures in 1975[26] decided to *define* the speed of light as

[26] https://www.bipm.org/en/CGPM/db/15/2/

$$c = 299792458 \text{ms}^{-1}$$

> The 15th Conférence Générale des Poids et Mesures (CGPM), **considering** the excellent agreement among the results of wavelength measurements on the radiations of lasers locked on a molecular absorption line in the visible or infrared region, with an uncertainty estimated at $\pm 4 \times 10^{-9}$ which corresponds to the uncertainty of the realization of the metre,
> **considering** also the concordant measurements of the frequencies of several of these radiations,
> **recommends** the use of the resulting value for the speed of propagation of electromagnetic waves in vacuum $c = 299792458$ metres per second.

The 17th General Conference on Weights and Measures in 1983 then redefined the meter as follows [27]:

[27] https://www.bipm.org/en/CGPM/db/17/1/

> 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 17th Conférence Générale des Poids et Mesures (CGPM), considering
>
> - that the present definition does not allow a sufficiently precise realization of the metre for all requirements,
> - that progress made in the stabilization of lasers allows radiations to be obtained that are more reproducible and easier to use than the standard radiation emitted by a krypton 86 lamp,
> - that progress made in the measurement of the frequency and wavelength of these radiations has resulted in concordant determinations of the speed of light whose accuracy is limited principally by the realization of the present definition of the metre,
> - that wavelengths determined from frequency measurements and a given value for the speed of light have a reproducibility superior to that which can be obtained by comparison with the wavelength of the standard radiation of krypton 86,
> - that there is an advantage, notably for astronomy and geodesy, in maintaining unchanged the value of the speed of light recommended in 1975 by the 15th CGPM in its Resolution 2 (c = 299 792 458 m/s),
> - that a new definition of the metre has been envisaged in various forms all of which have the effect of giving the speed

of light an exact value, equal to the recommended value, and that this introduces no appreciable discontinuity into the unit of length, taking into account the relative uncertainty of $\pm 4 \times 10^{-9}$ of the best realizations of the present definition of the metre,

- that these various forms, making reference either to the path travelled by light in a specified time interval or to the wavelength of a radiation of measured or specified frequency, have been the object of consultations and deep discussions, have been recognized as being equivalent and that a consensus has emerged in favour of the first form,
- that the Comité Consultatif pour la Définition du Mètre (CCDM) is now in a position to give instructions for the practical realization of such a definition, instructions which could include the use of the orange radiation of krypton 86 used as standard up to now, and which may in due course be extended or revised,

decides

1. **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.**
2. The definition of the metre in force since 1960, based upon the transition between the levels $2p_{10}$ and $5d_5$ of the atom of krypton 86, is abrogated.

Spectra

We will complete this together with the first section of module 8.

- Sunlight and Incandescent sources
- Atomic spectra (discharge tubes)
- Using spectroscopy to identify elements
- Information from Stellar spectra:
  - Surface temperature
  - Rotational and translational velocity
  - Density
  - Chemical Composition

Solutions and Marking schemes for questions

2020 Q18 HSC: Answer is B.
Multiple choice question on Foucault: C

Question on Maxwell from the 2019 HSC exam:

Question 25

Criteria	Marks
• Relates the model to predictions made by Maxwell	4
• Relates the model to a prediction made by Maxwell • Identifies another prediction made by Maxwell or another feature of the model	3
• Identifies prediction(s) made by Maxwell AND/OR • Identifies feature(s) of the model	2
• Provides some relevant information	1

Sample answer:

The model shows alternating electric and magnetic fields perpendicular to each other. This is consistent with Maxwell's prediction that a changing electric field produces a changing magnetic field and vice versa.

The model shows a wave propagating at velocity v. Maxwell predicted the existence of a range of waves with different wavelengths, all travelling with the same speed.

Answers could include:

The model shows an oscillating charge and an e/m wave emanating from it. This is consistent with Maxwell's prediction that an oscillating charge produces an e/m wave.

Ways in which this model differs from Maxwell's predications.

Question on the Aberration of Starlight (Bradley's measurement of the speed of light) from 2021 Ruse trial:

Question 31

Answer:

a) $v_{TG} = v_{RG}\, tan(\theta)$

Criteria	Marks
$v_{TG} = v_{RG}\, tan(\theta)$ (or equivalent equation)	1

Most students were able to do this question

Mark distribution:

Marks	0	1			
% students	5	95			

b) The orbital velocity of the earth is given by $v_E = \frac{2\pi r_E}{T} = \frac{2\pi \times 1.5\times10^{11}}{365.25\times24\times3600} = 3.0 \times 10^4 ms^{-1}$

The speed of light is $c = \frac{v_E}{tan(\theta)} = \frac{3\times10^4}{tan(0°0'20.5)} = 3.0 \times 10^8 ms^{-1}$

Criteria	Marks
Correctly calculates the orbital velocity of the earth Identifies the equation relating the speed of light, $\theta°$ and r_E, and substitutes correctly to calculate the speed of light.	2
Correctly calculates the orbital velocity of the earth OR Identifies the relationship between the speed of light, $\theta°$ and r_E	1

This question required students to:

- Recognise the analogy between the change in apparent direction of the rain for the moving observer in part a) and the change in the apparent direction of light from a star
- To convert the period from days to seconds
- To use v = 2πr/T to calculate the earth's orbital velocity
- To substitute these into an adapted version of their formula from part a)

Mark distribution:

Marks	0	1	2		
% students	17.7	12.5	71		

Question on Fizeau from the "Additional sample questions" for the new HSC syllabus:

Marking guidelines:

Criteria	Marks
• Explains why specific speeds will completely block the light • Supports answer with calculations	5
• Explains why a specific speed will block the light with relevant calculations	4
• Provides some relevant calculations AND/OR • Outlines how movements of the wheel can cause a tooth to completely block the light	2–3
• Provides some relevant information	1

Sample answer:

Light travels at 3.00×10^8 m s^{-1}, so for an 8 km journey to the mirror and 8 km back, the time taken will be:

$$t = \frac{s}{v}$$

$$\frac{2 \times 8000}{3.00 \times 10^8} = 5.33 \times 10^{-5} \text{ seconds.}$$

If the wheel is stationary, the light travelling through a gap will return completely through the gap, but if the wheel is rotating, a cog (tooth) will begin to block the returning light. If a tooth moves exactly the width of a gap in the time it takes the light to return, it will completely block the light.

It takes 5.33×10^{-5} seconds for the light to travel to the mirror and back. To completely block the light, the tooth will have moved into the path of a gap in this time. Since there are 50 teeth and 50 gaps, the wheel will have rotated 1/100th of a rotation in this time. This is equal to $2\pi/100$ radians.

The rotational speed of the wheel is given by $\omega = \triangle\theta / t$.

$$\omega = \frac{\frac{2\pi}{100}}{5.33 \times 10^{-5}} = 1180 \text{ rad s}^{-1}$$

Spinning the cogwheel at 3, 5 and 7 times this rate (or any odd multiple) would also completely block the returning light, as the light will be blocked by subsequent teeth.