Mastering Physics

MODULE 7

NSW

The Nature Of Light

Brian Shadwick

Science Press

First published 2020

Science Press
Unit 7, 23-31 Bowden Street
Alexandria NSW 2015 Australia
Tel: +61 2 9020 1840 Fax: +61 2 9020 1842
sales@sciencepress.com.au
www.sciencepress.com.au

Contents

The Electromagnetic Spectrum

7.1	James Clerk Maxwell	2
7.2	Transverse Electromagnetic Waves	4
7.3	Measuring the Speed Of Light	6
	Historical measurements of the speed of light	6
	Measuring the speed of light – home experiment	8
7.4	Comparing Spectra From Light Sources	9
7.5	Spectroscopy and Elements	11
7.6	Spectra Of Stars	13

Light: Wave Model

7.7	Diffraction	18
7.8	Young's Double Slit Experiment and Diffraction Gratings	21
	Young's double slit experiment	21
	Diffraction gratings	23
7.9	Models Of Light	25
	Newton's model of light	25
	Huygens' model of light	27
	The electromagnetic wave theory of light	29
7.10	Polarisation and Malus' Law	31
	Polarisation	31
	Types of polarisation	33
	Malus' law	35

Light: Quantum Model

7.11	Max Planck and Wilhelm Wien	38
	Max Planck – the beginning of quantum theory	38
	Wien's displacement law	40
7.12	Albert Einstein and the Photoelectric Effect	42
7.13	Analysing the Photoelectric Effect	44

Light and Special Relativity

7.14	History Of Relativity	48
	Relativity before Einstein – background information	48
	Frames of reference	52
	The principle of relativity	53
	Einstein's postulates	54
7.15	Einstein's Thought Experiments	56
	Einstein's first thought experiment	56
	Time dilation – Einstein's second thought experiment	58
	t_v or not t_v? That is the question!	59
	Length contraction	62
	Combined relativity questions	64
7.16	Validation Of Special Relativity	66
7.17	Relativistic Mass and Momentum	68
	Relativistic mass	68
	Relativistic momentum	69
7.18	Einstein's Mass-Energy Equivalence is included in Module 8	

Answers	70
Data Sheet	88
Formula Sheet	89
Periodic Table	90

ISBN 978-0-85583-8263

Words to Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

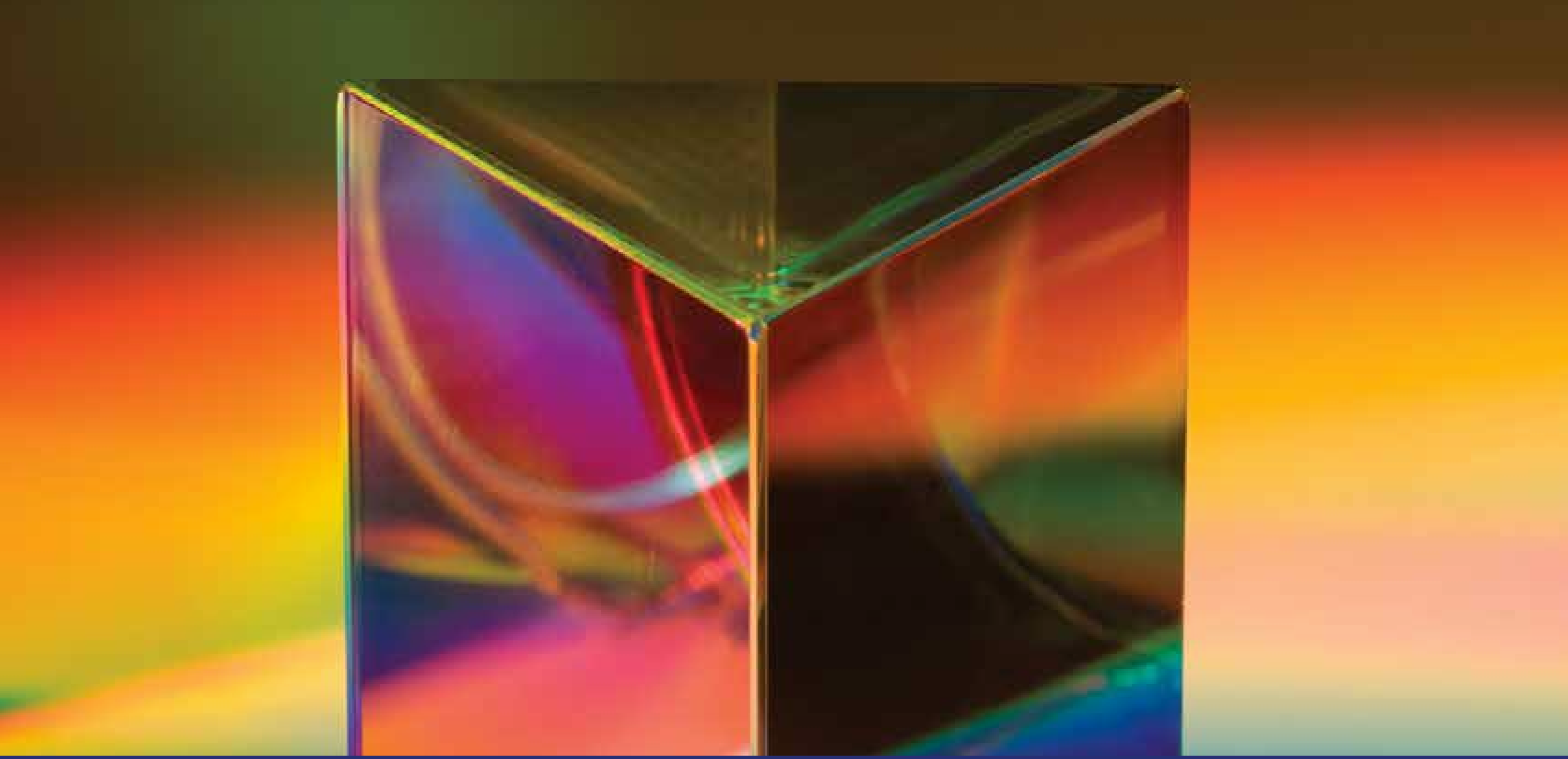
state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

ISBN 978-0-85583-8263



The Electromagnetic Spectrum

Science Press
MASTERING DOT POINT PHYSICS
ISBN 978-0-85583-8263

7.1 James Clerk Maxwell

Investigate Maxwell's contribution to the classical theory of electromagnetism, including unification of electricity and magnets, prediction of electromagnetic waves and prediction of velocity.

James Clerk Maxwell

1862 – Maxwell

Influenced by the work of Michael Faraday in the 1830s, proposed that the speed of an electromagnetic wave would be the same as the speed of light.

Proposed that light was a transverse wave in the same medium as electric and magnetic waves – this was known as the aether.

Developed a set of 20 simultaneous equations containing 20 variables that showed that electric and magnetic fields are two complementary components of electromagnetic fields.

1864 – Maxwell

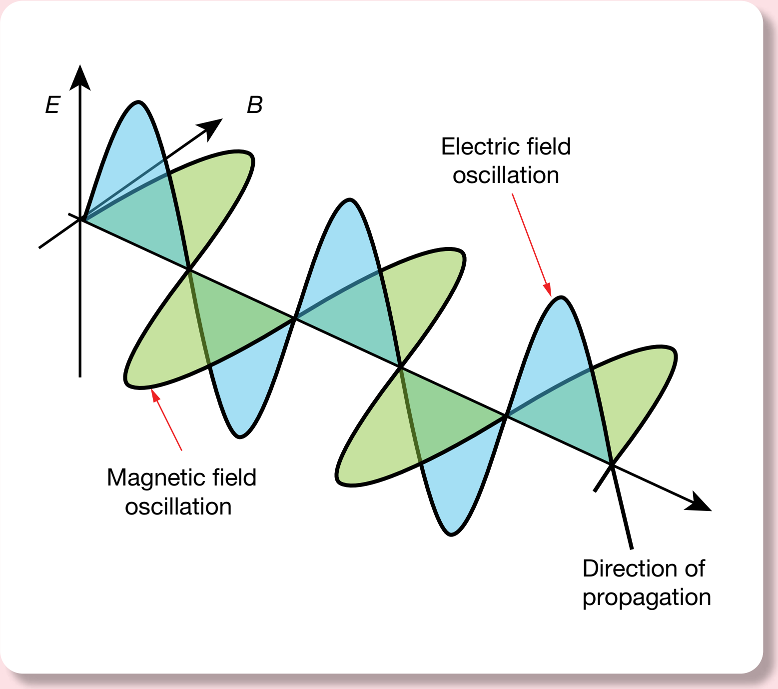
Puts forward his theory of electromagnetic radiation.

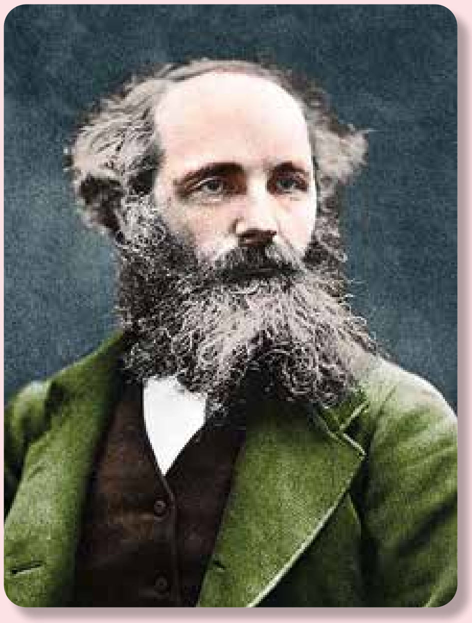
Electricity, magnetism, and light could all be explained using the same theory in physics.

Light was propagated by alternating electric and magnetic fields, which he believed would vibrate perpendicular to one another.

1867 – Maxwell

Made the first prediction that there would be a continuous range of electromagnetic radiations which extended beyond the visible spectrum at both ends.





James Clerk Maxwell
(1831-1879).

ISBN 978-0-85583-8263

Sample Questions

1. Complete the sentences below to summarise Maxwell's contributions to electromagnetic radiation by placing one word in each box.

(a) Around 1862, Maxwell proposed that the speed of propagation of an electromagnetic was ☐ ☐ as the speed of ☐.

(b) Maxwell proposed that light must be a ☐ in a medium which was the same medium carrying electrical and magnetic waves.

(c) In the 1830s Michael Faraday converted ☐ ☐ into ☐ energy using an insulated wire and a galvanometer.

(d) Faraday used the results of his experiment to derive electric and magnetic equations to describe ☐ and ☐.

(e) Maxwell understood the significance of Faraday's work and, in 1864 proposed a theory connecting ☐, ☐ and ☐ into a single theory.

(f) Maxwell's theory proposed that electricity, magnetism, and light could all be explained using the ☐ theory in physics.

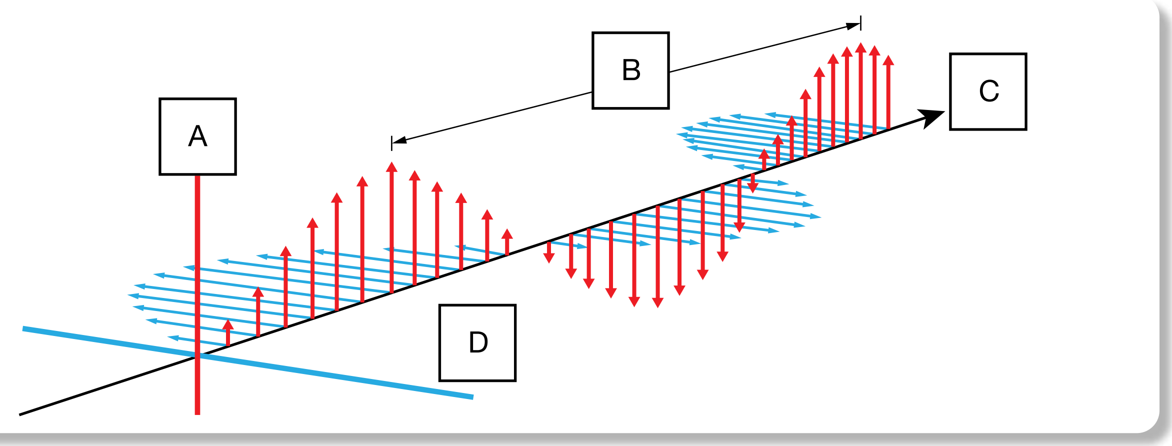
(g) Maxwell's theory also proposed that light was ☐ by alternating electric and magnetic fields.

(h) Maxwell believed that the alternating electric and magnetic fields would vibrate ☐ to one another.

(i) In 1867 Maxwell predicted that there was a ☐ ☐ of electromagnetic radiations.

(j) This was the first prediction of a continuous ☐ of electromagnetic radiation.

2. Identify the labelled parts of the diagram of an electromagnetic wave.



ISBN 978-0-85583-8263

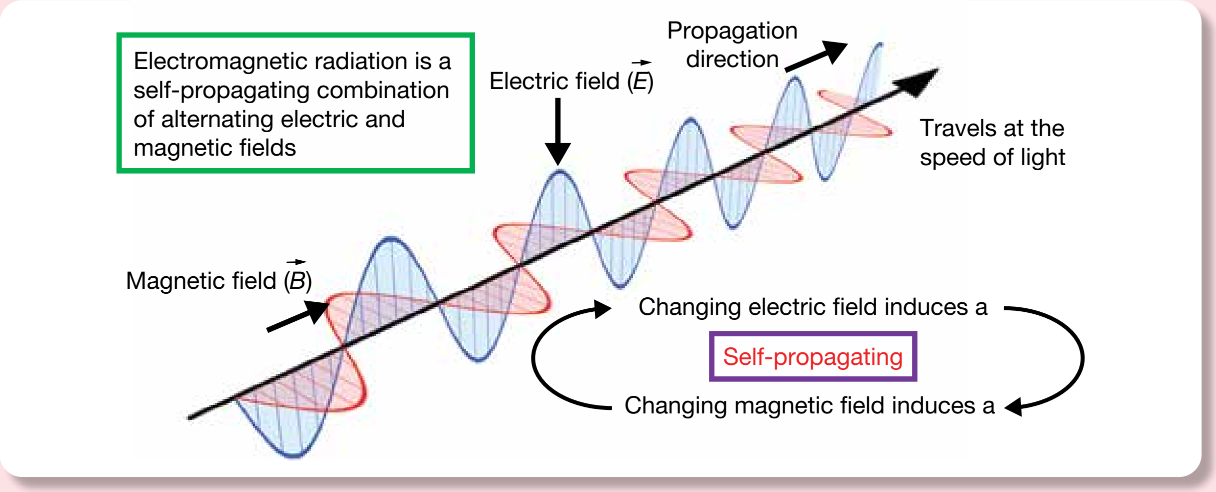
7.2 Transverse Electromagnetic Waves

Describe the production and propagation of electromagnetic waves and relate these processes qualitatively to the predictions made by Maxwell's electromagnetic theory.

Transverse electromagnetic waves

Electromagnetic waves

- Are self-propagating alternating induced electric and magnetic fields travelling through space at the speed of light, 3×10^8 m s^{-1}, slower through denser mediums.



Electromagnetic waves

- Can travel through a vacuum.
- Classified as transverse waves because the changing magnetic and electric fields are at right angles to the direction in which they carry energy.
- The **wavelength**, (λ), of an electromagnetic wave is the distance between the peaks of successive magnetic or electric field pulses.
- The **period**, (T), of an EMR is the time for one wavelength to pass a given point.
- The **frequency**, (f), is the number of wavelengths that pass a point each second. Frequency is measured in hertz (Hz).

- The energy carried by each EMR photon is directly proportional to the frequency of the radiation as given by Planck's quantum theory equation, $E = hf$, where f is the frequency of the wave and h is Planck's constant (see later).
- Note that the energy of an electromagnetic radiation photon is dependent on its frequency, *not* the amplitude of the electric and magnetic field oscillations.
- We refer to the **intensity**, (I), of an electromagnetic wave rather than to its amplitude. The intensity of an electromagnetic wave depends on the number of photons in the beam. Each photon will have energy dependent on its frequency. The more photons in a beam, the greater the intensity and the higher the total energy.

Science Press
MASTERING DOT POINT PHYSICS
ISBN 978-0-85583-8263

Sample Questions

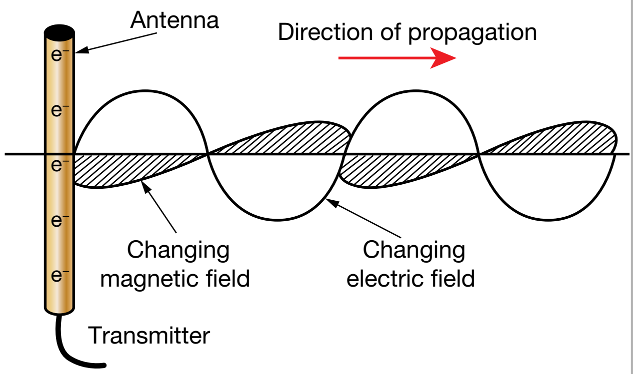
1. (a) What is an electromagnetic wave?

(b) State three ways in which an electromagnetic wave differs from transverse matter waves.

(c) Given that transverse waves are defined in terms of the relative direction of their particle oscillation, and that electromagnetic waves do not propagate through particle oscillation, why are they referred to as transverse waves?

2. Sheldon and his friends reflected a laser beam with speed 3×10^8 m s^{-1} off the Moon and received the reflected signal back on Earth 2.5 s later. According to this information, what is the distance between the Moon and the Earth?

3. The diagram shows an antenna emitting EMR.



In what way do the electrons in the antenna produce the EMR?

(A) By moving at constant speed upwards, only.

(B) By moving at constant speed downwards, only.

(C) By moving at constant speed alternatively upwards and downwards.

(D) By accelerating upwards and downwards alternatively.

4. What is the same for all EMR?

(A) Their amplitude.

(B) Their frequency.

(C) Their speed.

(D) Their wavelength.

5. What is the same for blue and yellow light?

(A) They have the same energy.

(B) They have the same frequency.

(C) They have the same speed.

(D) They have the same wavelength.

6. The Sun's rays travel through space:

(A) At the speed of sound.

(B) At twice the speed of sound.

(C) At half the speed of light.

(D) At the speed of light.

7. Which statement is true regarding mechanical and electromagnetic waves?

(A) Both types require a medium.

(B) Neither type requires a medium.

(C) A mechanical wave requires a medium, but an electromagnetic wave does not.

(D) EMR speed is affected by a medium, but the speed of a mechanical wave is not.

8. How does visible EMR from the Sun differ from the non-visible EMR from the Sun?

(A) It has different amplitudes.

(B) It travels a different distance.

(C) It travels at a different speed.

(D) It has different wavelengths.

9. What is the relationship between the wavelength (λ), and frequency (f), of an EMR?

(A) If λ increases, f increases.

(B) If f decreases, λ increases.

(C) If f remains constant, λ increases.

(D) If λ remains constant, f increases.

10. The range of electromagnetic waves placed in a certain order is called the:

(A) Electromagnetic spectrum.

(B) Electromagnetic wavelength.

(B) Electromagnetic frequency.

(B) Electromagnetic field.

11. What determines the energy carried by electromagnetic waves?

(A) Their amplitude.

(B) Their frequency.

(C) Their speed.

(D) The medium they travel through.

ISBN 978-0-85583-8263

7.3 Measuring the Speed Of Light

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.

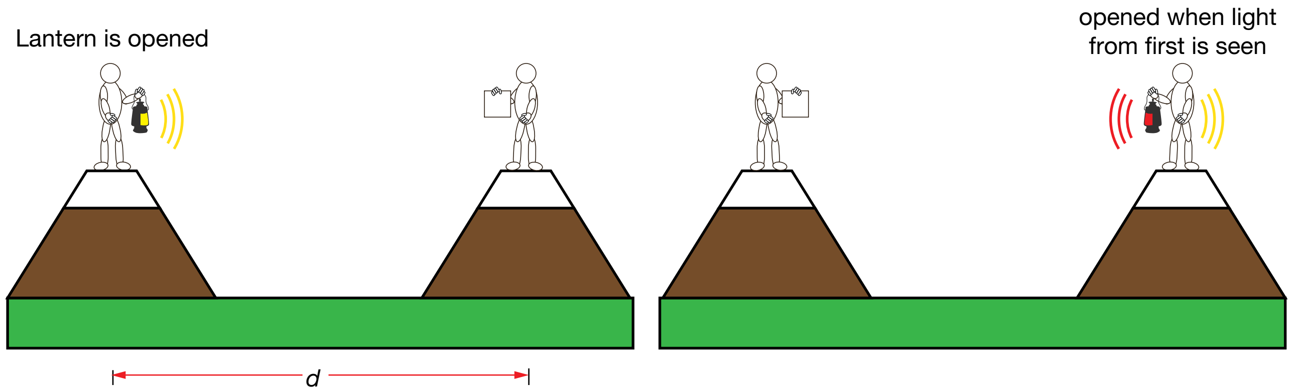
Historical measurements of the speed of light

Sample Questions

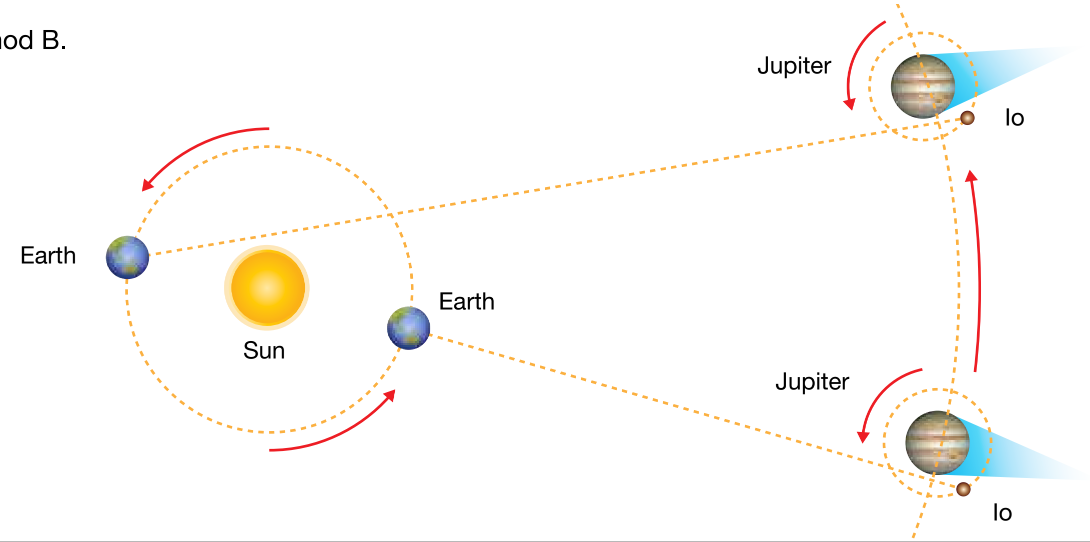
1. Each of the diagrams below represents one of the early methods used by scientists to measure the speed of light. Your task for each diagram is to:

- Determine which scientist used this method, and when he used it.
- Briefly describe the physics behind the method used.
- Indicate the answer he got and its degree of error taking the accepted value today (set in 1983) as 299 792 458 m s^{-1}. (Note the values you research will vary across resources.)

(a) Method A.

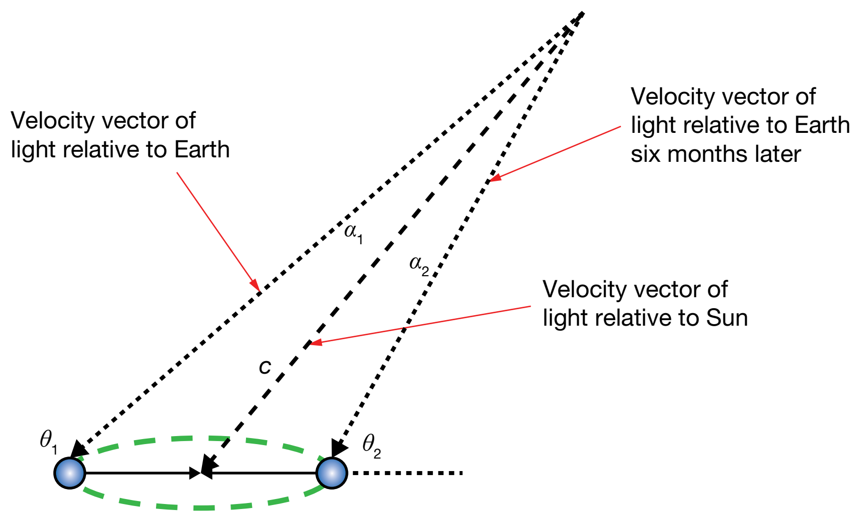


(b) Method B.

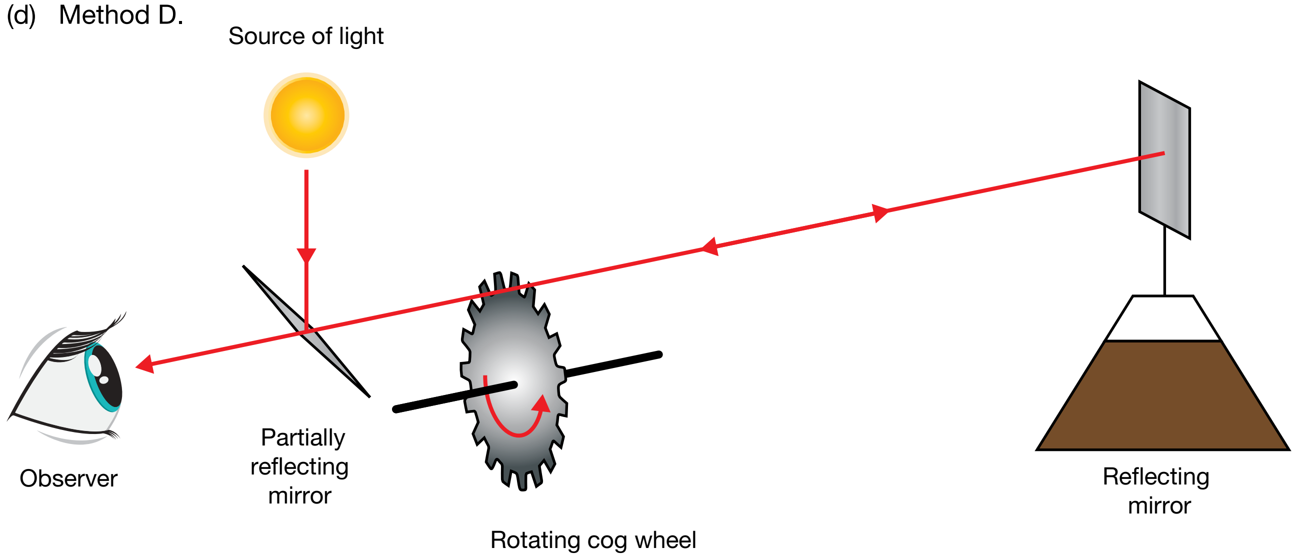


Science Press
MASTERING DOT POINT PHYSICS
ISBN 978-0-85583-8263

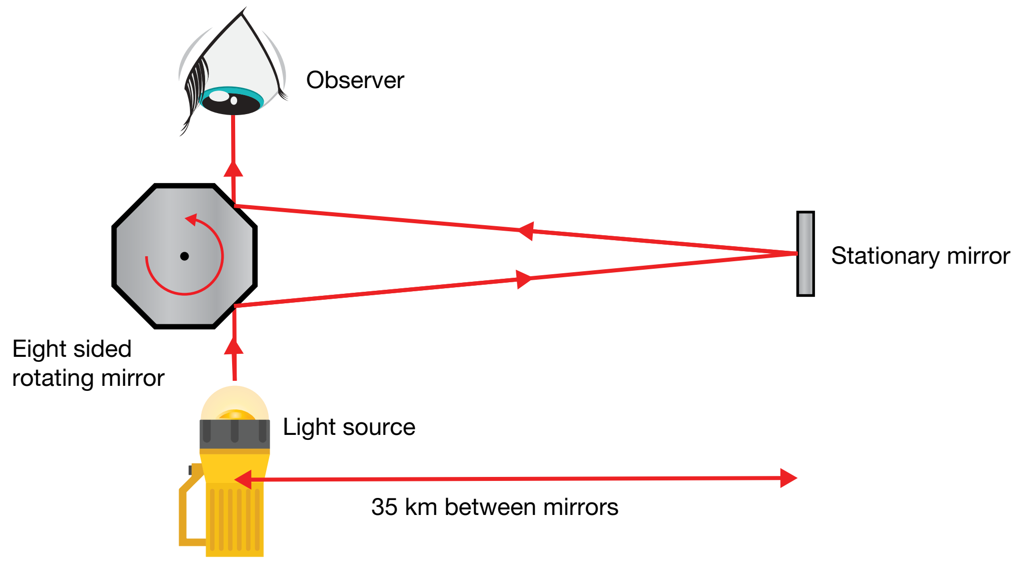
(c) Method C.



(d) Method D.



(e) Method E.



ISBN 978-0-85583-8263

Sample Questions

Melting chocolate and the speed of light

Some students took the baseplate out of a microwave oven and inserted a plate over the rotor so that when the oven was on the plate remained stationary.

They placed a bar of chocolate on the plate, closed the door, then turned on the oven, watching the bar through the door.

As soon as they noticed melt spots on the chocolate, they switched the oven off and removed the chocolate and the plate it was on from the oven.

Their results are shown in the photograph below.

1. Briefly, with the aid of a diagram, outline the physics of this experiment.
2. Knowing that the frequency of the microwaves emitted by this oven was 2500 MHz, use the students' results to calculate the speed of light.
3. Compare your answer to the accepted value = 299 792 458 m s^{-1}.
4. Comment on the validity of the experiment.
5. Comment on the reliability of the experiment including how this might be improved.

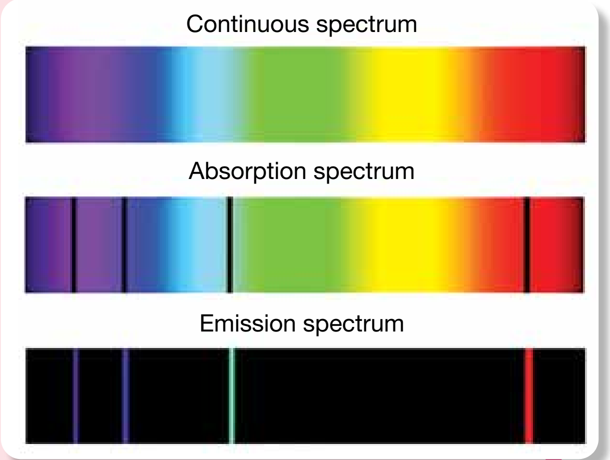
Science Press
MASTERING DOT POINT PHYSICS
ISBN 978-0-85583-8263

7.4 Comparing Spectra From Light Sources

Conduct an investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight or incandescent filaments.

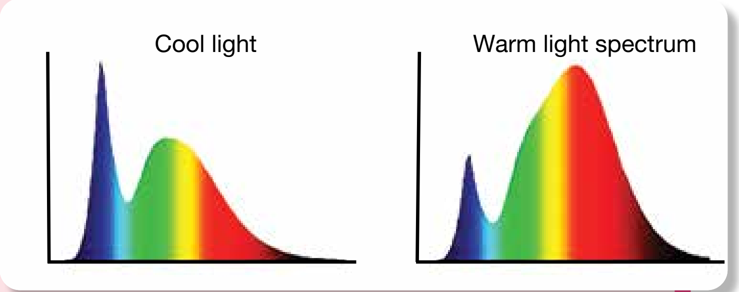
Comparing spectra from light sources

Emission, absorption and continuous spectra



- Spectra are formed when electrons fall from higher to lower energy levels.
- In doing this they emit electromagnetic radiation specific to the energy difference between the two levels.
- A hot, opaque object or hot dense gases, emits a **continuous spectrum**, with all wavelengths.
- Hot objects will also emit radiation specific to their elemental composition.
- If light from a continuous spectrum passes through a cool, transparent gas, dark lines appear in the spectrum because the atoms of the cool gas absorb wavelengths of light specific to those atoms. This is called an **absorption spectrum**.
- This allows us to determine the composition of the cool gas.
- Any light source and warm or hot object emits its own light forming an **emission spectrum**.
- An emission spectrum looks like the opposite of an absorption spectrum, with the bright emission lines at the same wavelengths as the dark lines in the absorption spectrum.
- The wavelengths of the lines in an emission spectrum are the same as the absorption lines in the spectrum (for the same gas).

The nature of spectra

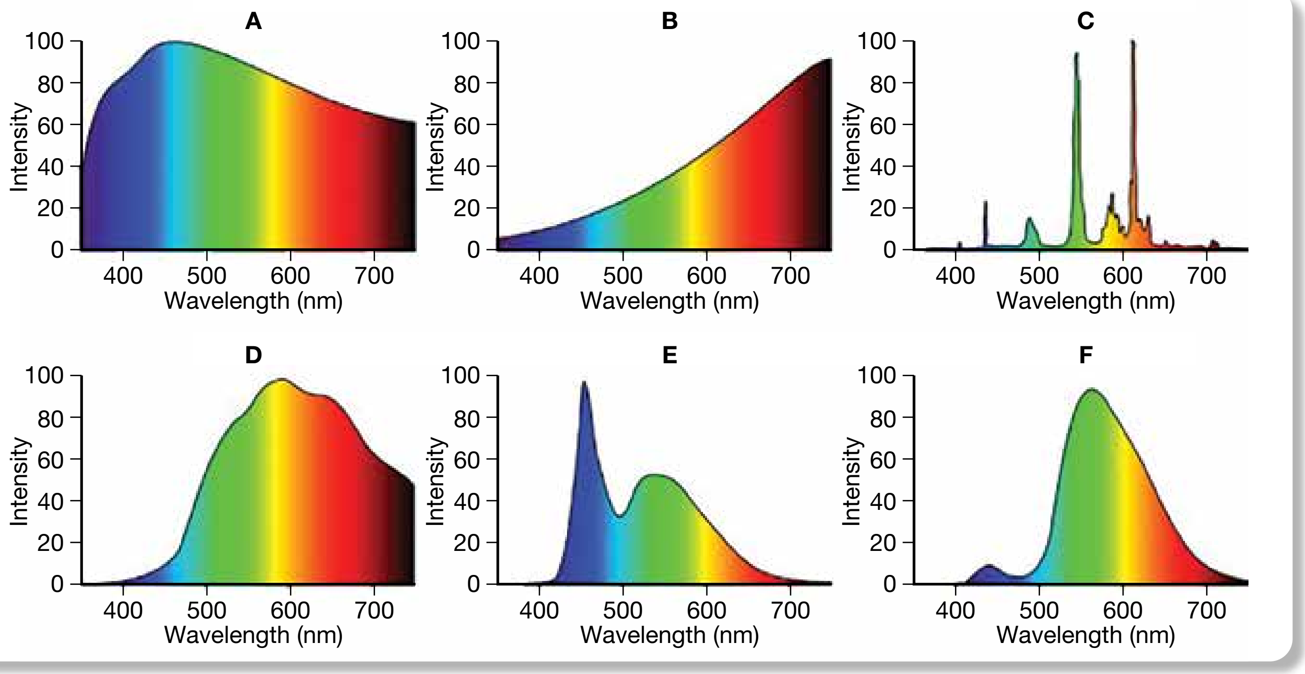


- Depends on the composition and temperature of the source.
- Light sources that have filaments that get very hot will produce continuous spectra.
- Low temperature vapour light sources such as mercury or sodium vapour lamps will produce light consistent with their composition rather than their temperature.
- Low temperature light sources made by different manufacturers will produce different spectra because they will not all be identical in composition.
- If the surface temperature is constant, the spectrum the object produces will be the same every time it is produced. The spectrum is a fingerprint for the object.
- '**Cool**' or white light sources will have a spectrum which gives out **more blue light** than yellow and red light.
- '**Warm**' lights emit more light in the yellow and **red** end of the spectrum.

ISBN 978-0-85583-8263

Sample Questions

The diagrams show the spectra from six different light sources. Use them to answer the questions below.



1. Which spectrum is produced by a hot, incandescent light? Justify your choice.

2. Which of the spectra is produced from the hottest light source? Justify your choice.

3. Would light source A be hotter or cooler than light source D? Justify your answer.

4. Explain why the light from source E is called a cool light.

5. Explain why the light from source F is called a warm light.

6. How do we know that light sources E and F are not incandescent light sources?

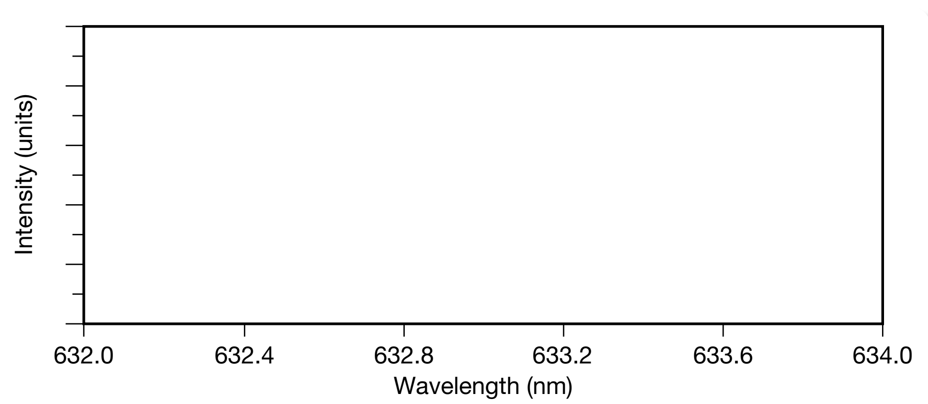
7. One of these spectra is from a light which is described as a 'daylight'. Which one, and why is it given this name? Use another relevant spectrum in your answer.

8. One of the spectra is produced by a fluorescent light (now no longer produced and used). Which one, and then account for the appearance of the spectrum it forms.

9. A red laser produces a coherent beam of red light with wavelength 633.0 nm.

(a) What does 'coherent' mean when used in this context?

(b) On the graph grid, draw in the spectrum you would expect to be formed from this source of light.



Science Press
MASTERING DOT POINT PHYSICS
ISBN 978-0-85583-8263

Answers

7.1 James Clerk Maxwell

1. (a) Around 1862, Maxwell proposed that the speed of propagation of an electromagnetic wave was the same as the speed of light.

(b) Maxwell proposed that light must be a wave in a medium which was the same medium carrying electrical and magnetic waves.

(c) In the 1830s Michael Faraday converted electric energy into magnetic energy using an insulated wire and a galvanometer.

(d) Faraday used the results of his experiment to derive electric and magnetic equations to describe electricity and magnetism.

(e) Maxwell understood the significance of Faraday's work and, in 1864 proposed a theory connecting light, magnetism and electricity into a single theory.

(f) Maxwell's theory proposed that electricity, magnetism, and light could all be explained using the same theory in physics.

(g) Maxwell's theory also proposed that light was propagated by alternating electric and magnetic fields.

(h) Maxwell believed that the alternating electric and magnetic fields would vibrate perpendicular to one another.

(i) In 1867 Maxwell predicted that there was a continuous range of electromagnetic radiations.

(j) This was the first prediction of a continuous spectrum of electromagnetic radiation.

2. A = electrical field – note that the convention is to label the magnetic field horizontally

B = wavelength

C = direction of propagation

D = magnetic field

7.2 Transverse Electromagnetic Waves

1. (a) An electromagnetic wave consists of self-induced alternating electric and magnetic fields which carry energy from one place to another.

(b) They can travel through a vacuum, they do not involve the oscillation of particles, and the energy they carry depends on their frequency rather than the amplitude of the oscillation of the particles.

(c) The self-induced electric and magnetic fields oscillate at right angles to the direction in which the energy is carried and the graphed magnitudes of these fields form a sinusoidal curve. Both of these are transverse wave properties.

2. From distance = (velocity × time) ÷ 2

$= 3 \times 10^8 \times 1.25$

$= 3.75 \times 10^8$ m

= 375 000 km (average = 384 000 km)

3. D

4. C

5. C

6. D

7. C

8. D

9. B

10. A

11. B

7.3 Measuring the Speed Of Light

Historical measurements of the speed of light

1. (a) Method A.

Galileo Galilei was the first person to attempt to measure the speed of light. In 1638 Galileo and an assistant each stood on a different hilltop with a known distance between them. Galileo opened the shutter of a lamp and his assistant opened the shutter of a lamp as soon as he saw the light from Galileo's lamp. Galileo attempted to measure the time between opening his lamp and seeing that of his assistant.

Using the distance between the hilltops and his pulse as a timer, Galileo could calculate the speed of light. He and his assistant tried this with different distances between them, but no matter how far apart they were, he could measure no difference in the amount of time it took the light to travel. Galileo concluded that the speed of light was too fast to be measured by this method. Galileo reported that the speed of light was at least 10 times faster than sound (about 3300 m s^{-1}).

(b) Method B.

In 1675, the Danish astronomer Ole Roemer (1644-1710) became the first person to actually measure the speed of light. Roemer was measuring the time taken for Io, a moon of Jupiter, to pass behind (be eclipsed by) the planet in order to measure its orbital period.

Io is eclipsed by Jupiter once every orbit, as seen from the Earth. By timing these eclipses over many years, Roemer noticed something peculiar. The time interval between successive eclipses became steadily shorter as the Earth in its orbit moved towards Jupiter and became steadily longer as the Earth moved away from Jupiter.

ISBN 978-0-85583-8263