Physics Factsheet

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The Nature of Electromagnetic Waves

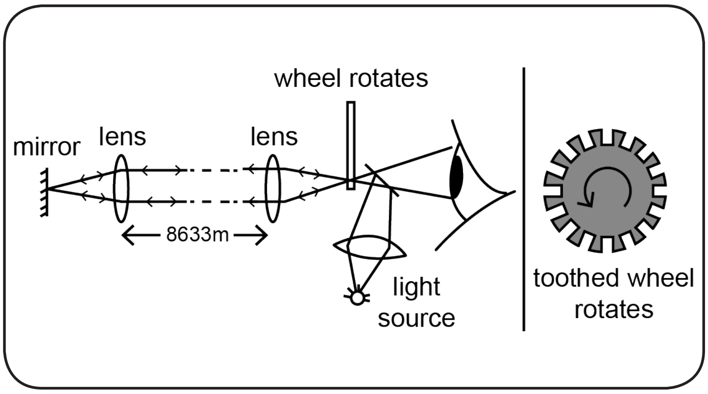
Many scientists have investigated the nature of electromagnetic waves. As light is the type of electromagnetic wave that we are most familiar with, it is hardly surprising that much of what we know about electromagnetic waves has arisen from investigating the nature and behaviour of light.

Measuring the speed of light

For example, our knowledge of the speed at which electromagnetic waves travel comes from investigations aimed at measuring the speed of light. Galileo attempted this as did Rømer and Bradley. One particularly important method used to calculate a value for the speed of light was done by Fizeau.

Fizeau used a "toothed wheel" apparatus, as shown below.

Figure 1



Light is brought to a focus and allowed to pass through the gap between two teeth of a gearwheel. The light is then formed into a beam and sent off to a mirror at a distance of several kilometres.

> ***Quick Question 1:** Why is it necessary to form the light into a beam like this?*

The light returns and is once more focussed so that it passes through the wheel. But the wheel has been rotating meanwhile, and if it is spinning fast enough a tooth will now be blocking the light path.

Fizeau wrote that when the wheel rotated at 12.6 revs/second, the light disappeared, but that at twice that speed it re-emerged, at three times the speed it disappeared, at four times the speed it re-emerged, and so on.

> ***Quick Question 2:** Why did this happen?*

Fizeau measured a speed of light of about 3.15×10^8 m/s in 1849. This is actually less accurate than an earlier calculation done by Bradley, but further refinements to the technique by Foucault and later Michelson, using a rotating mirror instead of a toothed wheel, brought the error down to plus or minus 4 m/s (about 0.001%) by 1926. Laser interferometry techniques eventually enabled the speed to be measured to within the nearest *millimetre* per second.

Clearly the speed of light was now known very precisely; in fact, it became possible to *define* the metre as the distance light travels in 1/299792458 in vacuo (this decision was taken in 1983). Thus, the speed of light, in vacuo, is fixed at 299792458 m/s.

> ***Quick Question 3:** What would happen if further measurements indicated that the speed of light was very slightly more than we had thought?*

What are electromagnetic waves?

At the beginning of the nineteenth century magnetism, electricity and optics were definitely three separate topics. But by the end of the nineteenth century, they had been combined into one theory of electromagnetism – a sort of Grand Unified Theory.

> ***Quick Question 4:** There are some thought-provoking similarities between magnetic poles and electrical charges though – suggest one or two.*

Magnetic fields

In 1820, Hans-Christian Oersted noted that a compass near a conducting wire would deflect when a current passed through the wire. In fact, all electrical currents produce magnetic fields (the invention of batteries by Volta and others made it much easier to produce currents and study their effects).

> ***Quick Question 5:** Sketch the magnetic field around a straight current and that through a solenoid.*

The magnetic field through a solenoid looks very much like that a bar magnet and the French physicist Ampère made the inspired suggestion that in fact *all* magnetic fields are created by the movement of charge on a microscopic level. This is essentially correct.

Ampère's Law describes how the magnetic field varies with the distance from the current. In the simple case of the circular field around a wire, we can write:

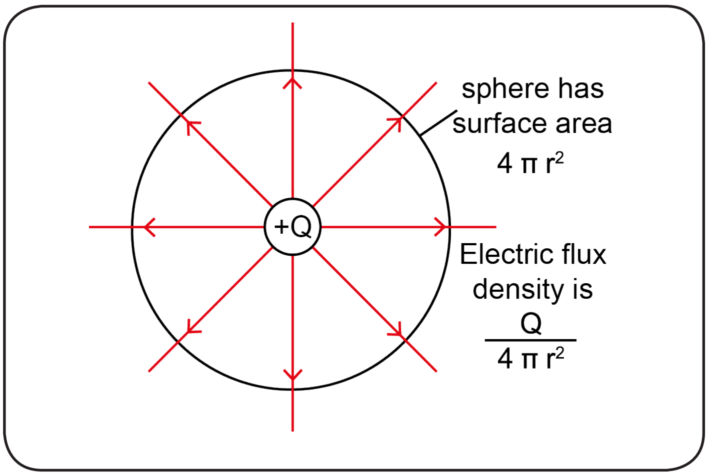
$$B = \mu_0 I / 2\pi r$$

B is the magnetic flux density, I is the current and r is the distance from the wire. The quantity μ_0 is known as the *magnetic permeability*. Roughly speaking, it is a measure of the magnetic response of a material. The greater μ is, the more magnetic flux will be produced in the medium by a given current – unsurprisingly, μ will be large for iron and much smaller for most other materials. In a vacuum, we give it the symbol μ_0 and call it the *magnetic permeability of free space*.

Electric fields

We can look at electrical fields in a similar way. Below is a picture of electrical field lines produced by a spherical charge Q:

Figure 2



We can see that the lines ("lines of electrical flux") spread out over a spherical surface of area $4\pi r^2$. The electrical field is proportional to the number of lines per unit area.

> ***Quick Question 6 :** Write down the equation for the field strength around a spherical charge +Q in a vacuum.*

Rather as in the magnetic case, we have a quantity ε called the "permittivity" – in different mediums, a different electrical field strength will be generated. In a vacuum, we have ε_0 – the "permittivity of free space".

Magnetic fields, electric fields and electromagnetic waves

Michael Faraday discovered both that a magnetic field exerts a force on a current (the "motor effect") and also that a **changing magnetic field will induce an e.m.f. ("Faraday's Law of Electromagnetic Induction")**.

Our picture of magnetic and electrical field lines in space is largely down to Faraday, whose powerful visual imagination and intuition compensated for his lack of early education in mathematics. He suspected that electricity and magnetism were closely connected to light, but was unable to demonstrate this.

James Clerk Maxwell is one of the greatest figures in the history of physics, comparable to Newton and Einstein. He made many advances in many different fields – electromagnetism, thermodynamics and colour theory among others. Casting Faraday's ideas into fully mathematical form, he also contributed a major physical insight in realising that just as a current could cause a magnetic field around it (Oersted's discovery), **so could a changing electrical field**.

So, if a changing magnetic field could induce an electrical field (Faraday's law) and a changing electrical field could induce a magnetic field (Maxwell's new addition to Ampere's law), **changing magnetic and electrical fields could propagate across empty space**.

He encoded these ideas in a series of mathematical formulae which are still known as **Maxwell's equations**. Using these, he was able to generate a relatively simple relationship which predicted that waves – that is, travelling oscillations – of the magnetic and electrical fields would propagate across space. The equation also predicted the speed at which these waves would travel. It turned out to be:

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

> ***Quick Question 7:** The value of ε_0 (permittivity of free space) is 8.85×10^{-12} F/m. The value of μ_0 (permeability of free space) is 1.26×10^{-7} H/m (or $4\pi \times 10^{-7}$ H/m). Hence calculate v.*

Maxwell concluded from this that the propagating electrical and magnetic fields **were light**. Light consists of oscillating magnetic and electrical fields travelling across space at a speed of $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$.

This is why we call it "electromagnetic radiation".

Implications

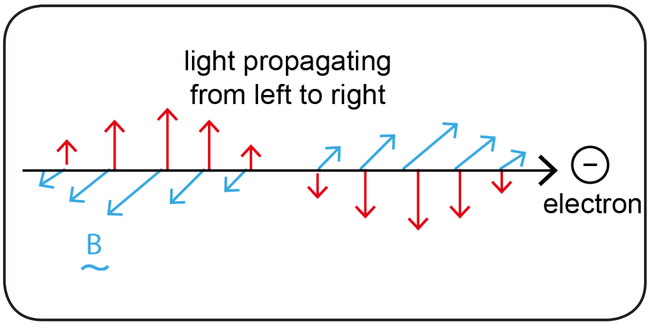
In his investigations of light, Young had rather accurately estimated the wavelength of red light as 1/36000 inch (700 nm) and that of violet light is about half as much. Maxwell's equations, however, suggested that electromagnetic radiation of *any* wavelength should be possible and of course this gives rise to what we now call the *electromagnetic spectrum*.

> ***Quick Question 8:** List the various forms of electromagnetic waves in order, from lowest to highest wavelength.*

*A diagram of an electromagnetic wave frozen in flight, as it were, might look like the diagram on the below. Note that the electrical and magnetic fields are **in phase** – their peaks coincide.*

***Quick Question 9:** What will happen to the electron as the wave passes it and why?*

Figure 3



A charged particle can thus absorb the energy of an electromagnetic wave. You could say that the interaction between charges and electrical fields is the *coupling* by which light and matter interact.

However, the reverse can also happen. If an electrical charge is accelerating, for example by oscillating up and down, it will distort the electrical field around it. This will set off a propagating electromagnetic wave – it will *emit* electromagnetic radiation.

Hertz and Marconi

One practical implication of this is that if we deliberately cause an electrical charge to oscillate at a particular frequency, it will give off electromagnetic radiation of this frequency. This radiation will travel across space at the speed of light. If it then encounters a metal rod (an aerial) then the varying electrical field will cause the electrons in the rod to oscillate back and forth.

> ***Quick Question 10:*** *What will this motion of electrons produce?*

This is how a radio or TV aerial works. An alternative type of aerial involves a coil of wire wrapped around a core of magnetic material – in this case it is the varying magnetic field which induces an e.m.f. in the coil (remember Faraday's Law of electromagnetic induction).

This was first demonstrated in the 1880s by Heinrich Hertz. Using an induction coil and capacitor to generate an oscillating signal, he created (what we would now call) radio waves. These travelled the few yards across his laboratory to a detector, where they produced a potential difference across a gap between two terminals. A small spark was observed when this happened.

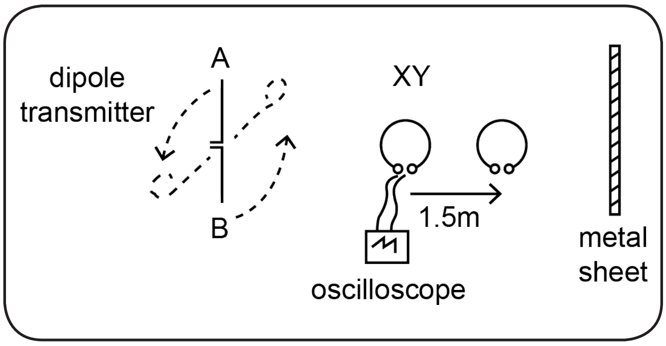
Hertz was also able to measure the speed of the radio waves. A sheet of metal was positioned to reflect them, thus forming a standing wave. By moving his detector away from the sheet to find the positions of the nodes and antinodes, he could measure the wavelength of the light. Knowing the frequency, he could calculate the speed using $v = f\lambda$.

Hertz saw this purely as a scientific demonstration rather than having any technical application – "it simply shows that Maestro Maxwell was correct", he said. However, others were quick to see the implications: Marconi famously developed the principles into practical "wireless telegraphy" – essentially Morse code by radio – and Fessenden pioneered the more flexible "continuous wave" system which might be considered the ancestor of modern radio.

Exam Style Questions

1) Apparatus similar to that shown below was used by Hertz to calculate the speed of radio waves.

Figure 4



a) The detector is moved from position X to position Y, a distance of 1.5 metres. As this happens, the intensity of the trace on the oscilloscope goes from a maximum to a minimum and returns to a maximum. Showing your working, calculate the frequency of the radio waves being produced. **(3)**

b) Briefly explain how the circular loop detects the radio waves. **(2)**

c) The transmitting aerial AB is now gradually rotated through 90 degrees so that it lies along the line CD. As this happens, the reading on the oscilloscope gradually drops to zero. Explain why this happens. **(3)**

d) A better detector may be constructed by winding many turns of copper wire around a ferrite rod (ferrite has similar magnetic properties to iron). Explain two advantages of this design. **(4)**

2) Fizeau's apparatus is used to calculate the speed of light. He found that if a wheel with 720 teeth were rotated at 12.6 revs/s, no reflected light would be seen by the observer, whereas at 25.2 rev/s, the reflected light would be at its brightest.

a) Showing your working, use these measurements to calculate the speed of light. **(4)**

b) Assume that the teeth are the same width as the gaps between them. State and explain what the observer would see as the rotation speed was gradually increased from 12.6 rev/s to 25.2 rev/s. **(3)**

Answers to Quick Questions

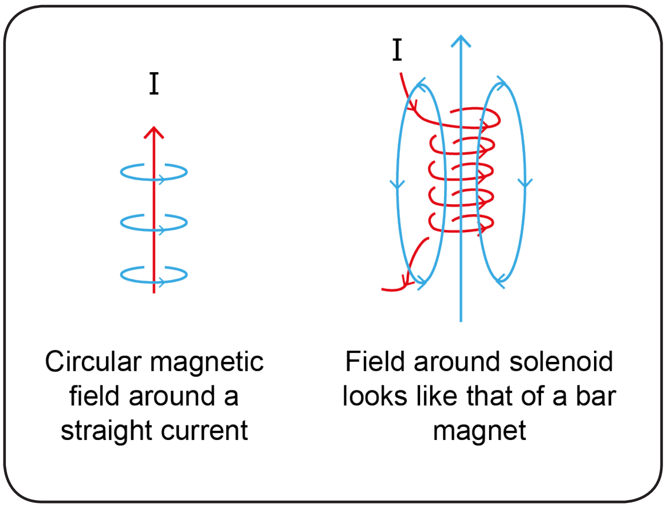
1) If the light is allowed to spread out, it will lose intensity as its energy is spread over a wider and wider area. By collimating it into a beam like this, this problem is avoided and it is still bright enough to see clearly after the 17km round-trip. A similar trick allows the 40W transmitters of Voyager 2 to be picked up from beyond the orbit of Neptune.

2) The wheel is rotating while the light is travelling, and at 12.6 revs/s the next tooth has enough time to move into a position where it blocks the returning light. However, if you double this rate of rotation, the next gap between teeth will have arrived, allowing the light to pass through and be observed. Odd multiples of 12.6 will correspond to teeth blocking the light and even multiples to gaps allowing it through.

3) Since the speed of light has now been fixed as described, this would affect the definition of the metre, which would accordingly become longer.

4) For example, opposite charges attract while like charges repel – similarly, opposite magnetic poles attract and like poles repel. Both forces can act at a distance but become weaker as distance increases.

5) **Figure 5**



6) Field strength = $Q/4\pi\varepsilon_0 r^2$
7) Plugging in the numbers should give 3.00 x 10^8 m/s to 3 significant figures!
8) Gamma rays, X-rays, ultraviolet, visible light, infra-red, microwaves, radio waves. These divisions are rather arbitrary of course and the radio region in particular could be subdivided further.
9) The electron experiences an electrical field first downwards, then upwards. Since it is negatively charged, it will feel a force first upwards, then downwards. It will begin to oscillate.
10) This is an alternating current

Answers to Exam Questions

Q1a	The detector is moving from one antinode (of magnetic field) to another	**1**
	Which is a distance of half a wavelength/ wavelength is 3.0m	**1**
	Thus frequency is 3.0 x 10^8 m/s / 3m = 1 x 10^8 Hz	**1**
Q1b	The radio wave consists of varying electrical and magnetic fields	**1**
	The varying magnetic field through the loop induces an e.m.f. around the loop of wire	**1**
Q1c	The direction along which the electrical field is varying is now along CD rather than AB OWTTE	**1**
	Magnetic field variation is at right angles to electrical field variation	**1**
	Thus flux linkage through the detector loop is now zero / magnetic field is now parallel to the detector loop instead of perpendicular to it	**1**
	Therefore no e.m.f. is induced	**1**
Q1d	The ferrite rod amplifies (and directs) the magnetic field lines	**1**
	So (rate of change) of magnetic flux linkage through the coil is greater	**1**
	Many turns of wire on coil mean magnetic flux linkage is greater / each turn of wire has an e.m.f. generated in it so we have several e.m.f.s in series	**1**
	So a greater e.m.f. is induced (hence stronger signal)	**1**

Q2a	Distance travelled = 17.3km	**1**
	Time taken = 1 / 25.2 s^{-1} x 720	**1**
	Speed = distance/time = 3.13 x 10^8 m/s	**1**
Q2b	The perceived intensity of light should gradually increase (Allow "the light would begin to flicker, with the duration of each flash steadily getting longer", although in fact the flicker would be too rapid to perceive)	**1**
	At first the tooth would be rotating to a position where it still blocks most of the light passing through the previous gap	**1**
Q2c	But as the rotation speed increases, less and less light will be blocked by the tooth	**1**

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