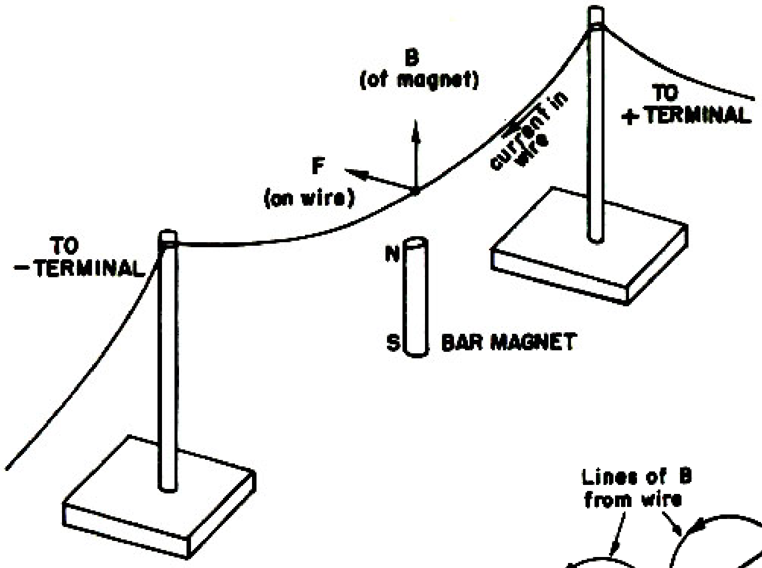
UNITING THE ELECTRIC & MAGNETIC FIELDS

The EM FIELD: Experiments on Magnetic Fields I

It is useful to see how we can investigate the relationship between electric and magnetic fields & forces using simple experiments. Here one such set-up is shown. In the top experiment a wire carrying current generates a field which interacts with the bar magnet, and a force is exerted on the wire, perpendicular to both current and to the field generated by the bar magnet… in the lower expt. we verify that this is a bona fide force, by showing that there is an equal & opposite force generated on the bar magnet coming from the field generated by the wire current.

Thus whatever is causing these forces, they are genuine forces in the sense described by Newton. Note that they are acting at a distance, via the vacuum.



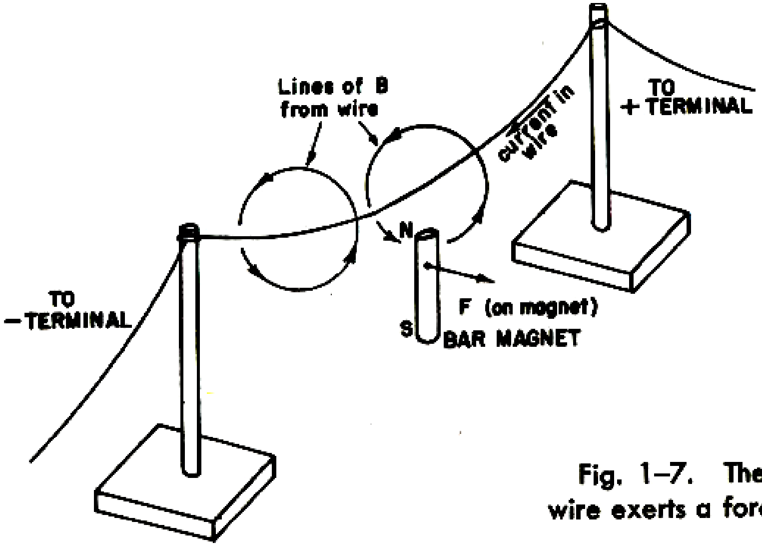


Fig. 1–7. The magnetic field of the wire exerts a force on the magnet.

The EM FIELD: Experiments on Magnetic Fields II

One may continue in this vein by looking at the interaction between 2 current-carrying wires. In the top picture we see how this works for 2 parallel currents- they actually attract each other. If we now replace the bar magnet from the last page with a solenoid-shaped wire carrying current, we find that it behaves just like the bar magnet.

In this way we establish that

(i) Electrical currents (ie, motion of electric charges) is what generates magnetic fields.

(ii) these fields in their turn act on electric currents. In this way 2 currents can interact over the space between them.

(iii) A permanent magnet behaves as though it were itself a set of aligned currents- actually, like a set of current loops.

(iv) the EM field hypothesis enables us to explain the existence of the bona fide forces which act on both charges and currents.

There is more……..

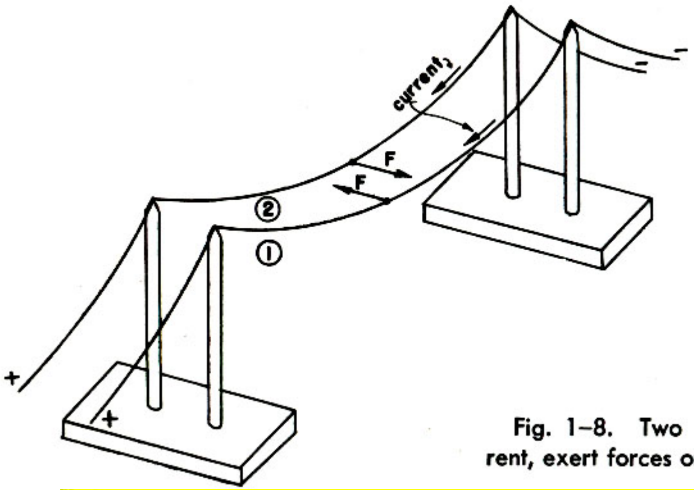


Fig. 1–8. Two wires, carrying current, exert forces on each other.

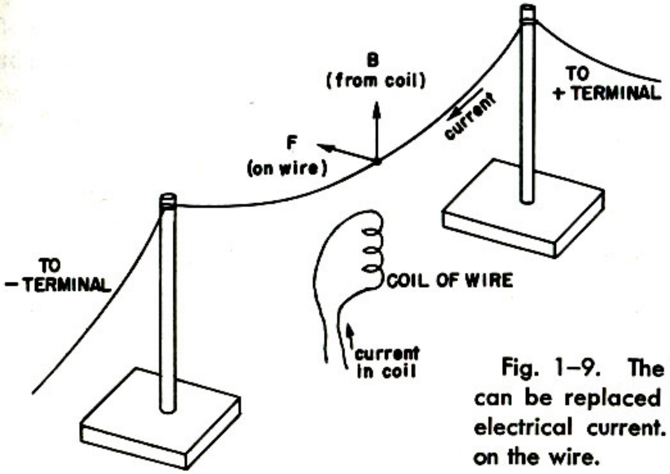
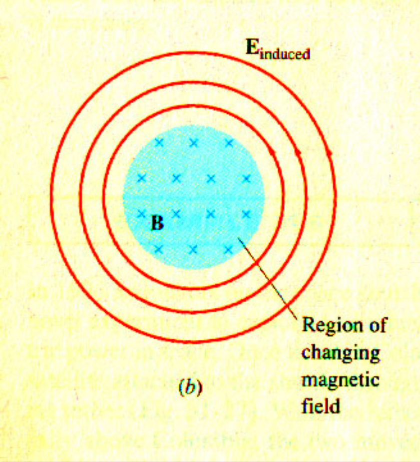
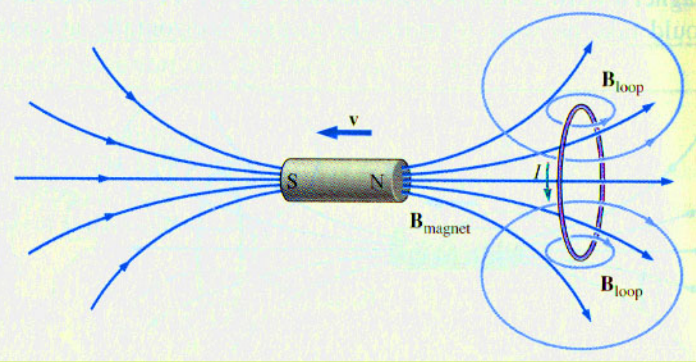


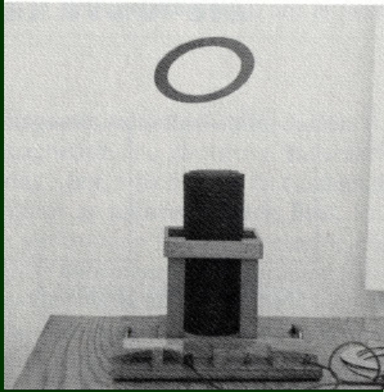
Fig. 1–9. The bar magnet of Fig. 1–6 can be replaced by a coil carrying an electrical current. A similar force acts on the wire.

ELECTROMAGNETIC INDUCTION

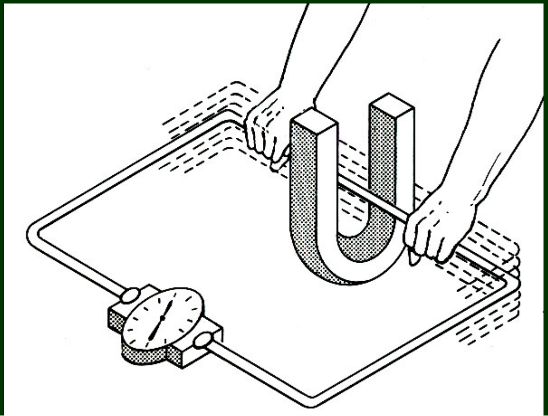


Electric field around changing B-field

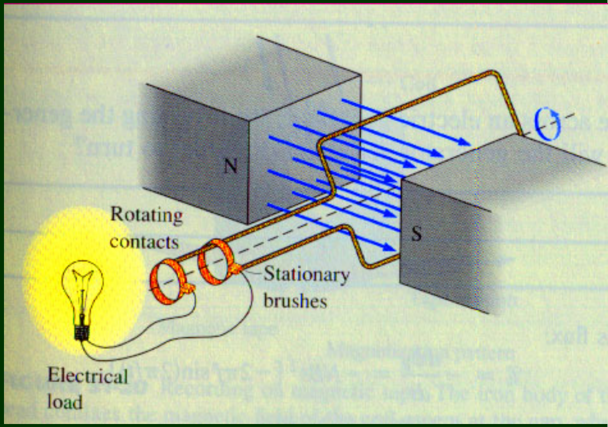




Suppose we now CHANGE a magnetic field in time…there are many ways to do this, shown in the various figures. We can change the total field through a current loop by moving the loop in the field(top right & bottom left), or by changing the current through the solenoid which is generating the field (see photo- the loop in this field is then projected into the air). We find that the changing total “amount of field”, or MAGNETIC FLUX, through the loop, causes an electric field (see above) which drives current around the loop- notice that this can be used to provide power (below right, where turning the loop in the field changes the flux through the loop) .

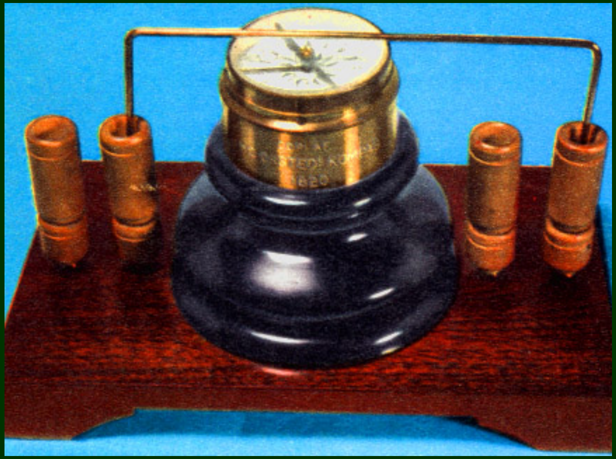


To summarize- changing the magnetic field creates an electric field. Likewise we saw that changing an electric field (eg., by moving charges) causes a magnetic field.



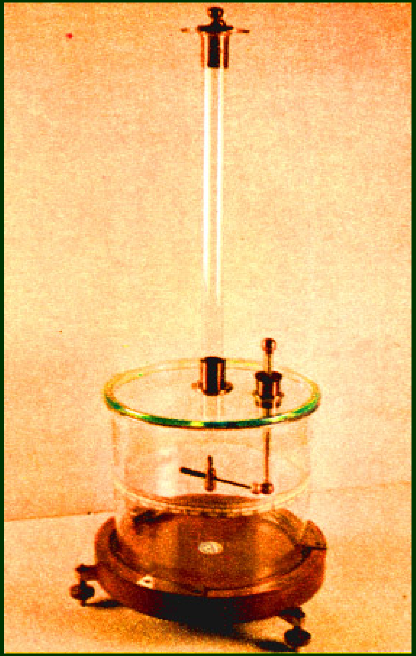
CRUCIAL EXPERIMENTS

Many physicists of the 19th century contributed to the understanding of EM phenomena. This involved the invention of new kids of apparatus for storing charge, generating currents, and measuring electric and magnetic fields- at the time unknown concepts.



Apparatus of Oersted

H.C. Oersted (1777-1851)



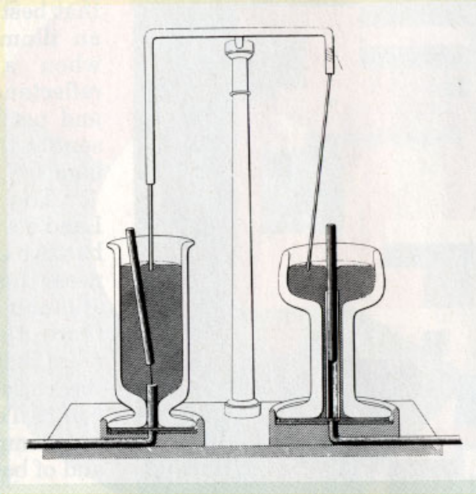
Coulomb's electro-static apparatus

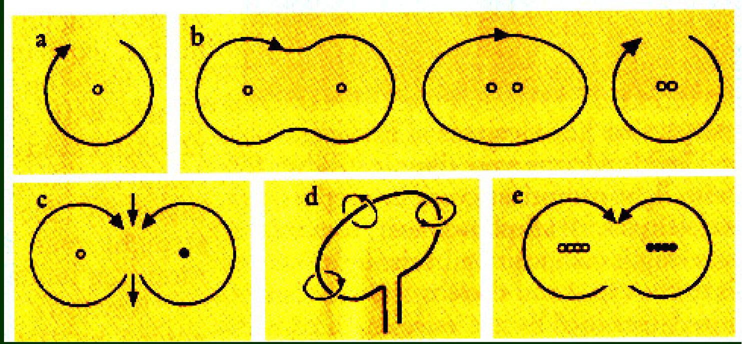
A. Coulomb (1736-1806)

Some examples are shown- the apparatus of Oersted to measure the direction of fields near a current-carrying wire, and Coulomb's device in which charge is stored on 2 light gold leaves whose deflection from each other is proportional to the stored charge. These were early experiments- things became more sophisticated later on. Note that a separation between theory and experiments was hardly relevant here- the investigations involved both, in a kind of detective story- although the work in countries like France was done by physicists with considerable mathematical training (unlike Faraday in London, who lacked even a high school education!).

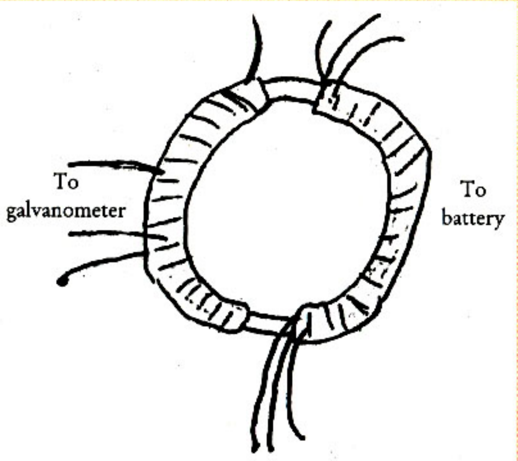
A.M. Ampere (1775-1836)

The Great Synthesis → EM FIELD

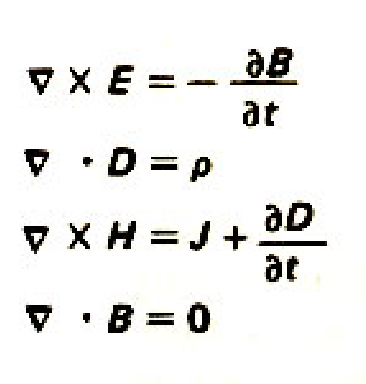




Faraday, with his many experiments and his concept of electric and magnetic “lines of force”, was able to put all the experimental work into a coherent whole. The figures show his apparatus for mapping B-fields (left) the results for current wires (above), and the induction of current in one loop by a changing current in another (see right).



Thus was the way prepared for the great theoretical synthesis of Maxwell, who postulated a single entity, the Electromagnetic field, with sub-components **B** (magnetic field) and **E** (electric field) . A modern writing of Maxwell’s theory appears in the form of a set of equations which can only be understood in the language of vector calculus- or an even more compact equation in terms of tensor calculus.



$$\nabla \times E = -\frac{\partial B}{\partial t}$$

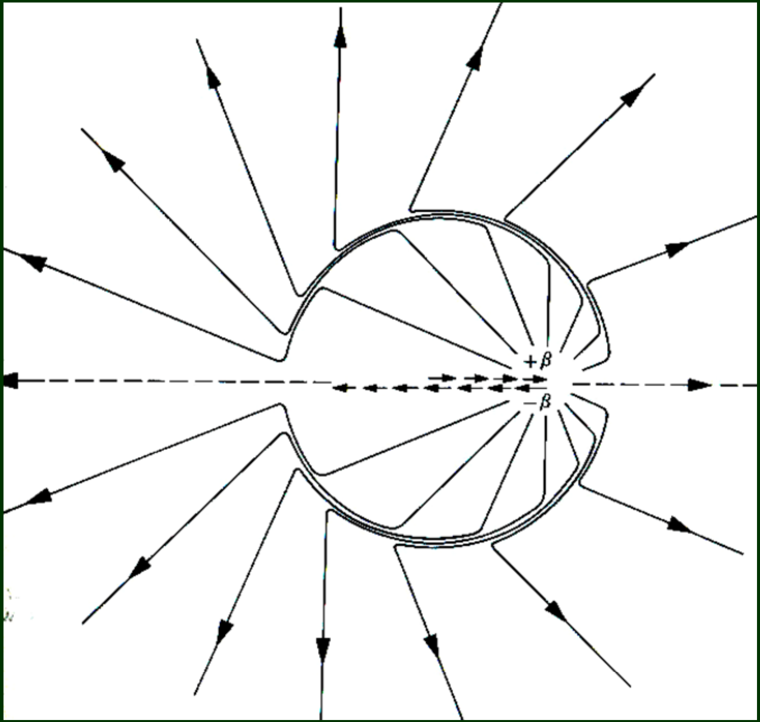
$$\nabla \cdot D = \rho$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \cdot B = 0$$

Like any real theory, Maxwell’s had predictive power- it implied the existence of phenomena and of relations between them, which were previously unexpected and surprising. The most obvious of these was EM waves…. (next slide)

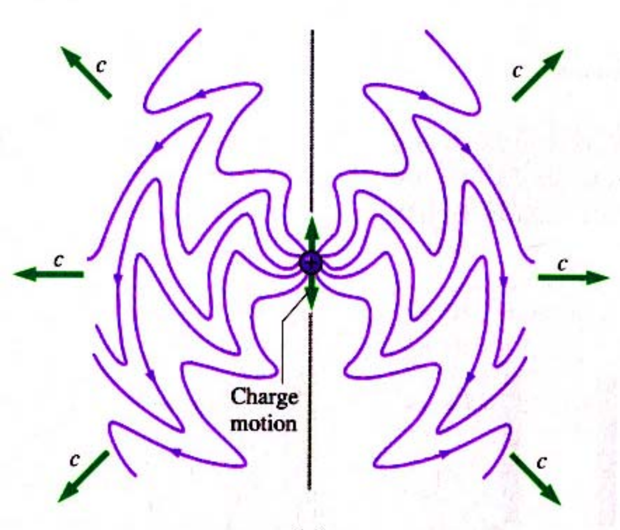
The EM FIELD: Electric & Magnetic Fields together



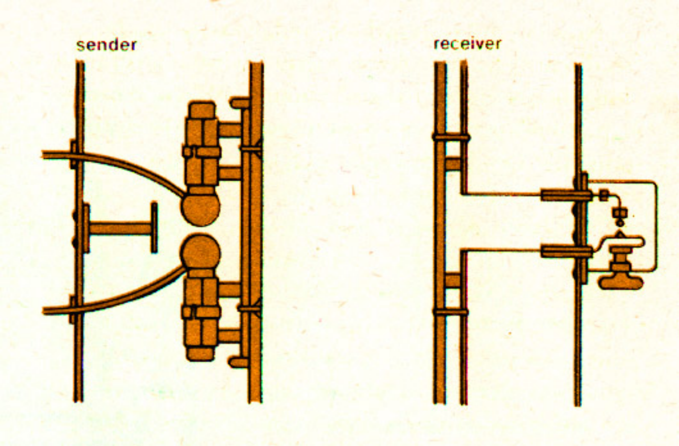
Suppose we now take a single charge and move it. The first thing we can ask is how the electric field will vary. At left we see what happens if a charge is suddenly moved to the right- the field readjusts to the new position of the charge, but we assume that the change in the field can only propagate at a finite speed. If the velocity of the moving charge approaches this propagation velocity, then we get something resembling a shock wave. An observer outside this will see the field as if the charge had not yet moved.

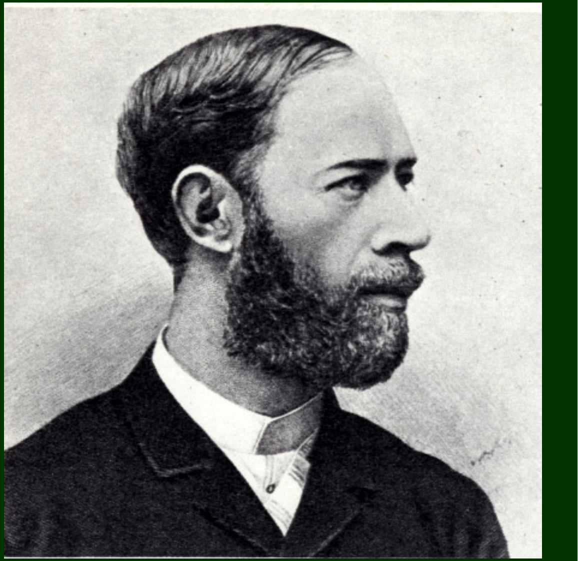
If we now cause the charge to oscillate (see right) a wave-like distortion of electric field is produced, which also moves out at some velocity- called here c.

We have already seen that a time-varying electric field causes a magnetic field- which itself is time-varying here. One sees that the net result will be a wave motion in which both fields are oscillating, and moving at velocity c.



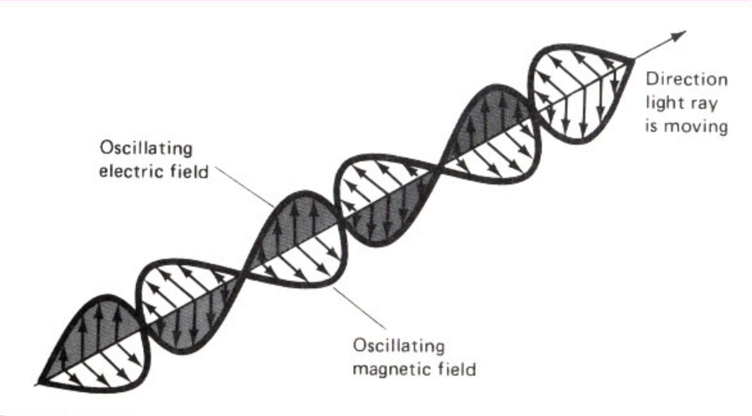
ELECTROMAGNETIC WAVES



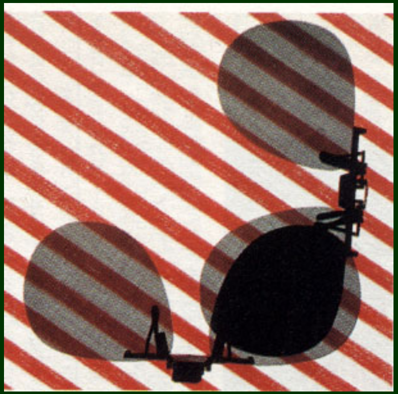

H. Hertz (1857-94)

The demonstration of the fact that EM waves existed came from H. Hertz in 1885; a spark in one circuit was picked up in another one some distance away. As predicted by Maxwell, the velocity was that of light (already measured accurately by many, beginning with Roemer in 1660).

Maxwell's theory predicted that light was a TRANSVERSE wave- the oscillations of B & E were in a direction transverse to the direction of propagation of the wave (and the 2 fields were exactly out of phase with each other). At the time it was assumed these were waves through a medium (called the 'ether').



The transverse nature of the waves can be seen in polarised light. Some materials only transmit light if the E-field oscillates in a certain direction. 2 perpendicular such glasses stop all light



The EM SPECTRUM

The decades that followed Maxwell's theory led to a slow extension of the frequency/ wavelength range studied & used- indeed, the rise of technology in the 20th century is based on this. Much of modern technology involves signal transmission and reception in some part of the EM spectrum. Most of our understanding of the universe is based on study of EM radiation, from gamma rays to the microwave background.