

MAXWELL DISCOVERS LIGHT IS ELECTROMAGNETIC WAVES



James Clerk Maxwell was a Scottish scientist. He worked in the mid-nineteenth century in Scotland and England. At that time, electricity and magnetism had been extensively studied, and it was known since 1831 that electric current produces magnetism. Maxwell added the idea that changing magnetism could produce electricity. The term that Maxwell added to the known equations (called Ampere's law) for magnetism allowed Maxwell to see that there were wave-like solutions, that is, solutions that look like a sine wave (as a function of time).

The numbers in Maxwell's equations all came from laboratory experiments on electricity and magnetism. There was nothing in those equations about light, and radio waves were completely unknown at the time, so the existence of electromagnetic waves was also completely unknown. But mathematics showed that Maxwell's equations had wave-like solutions. What did that mean?

Maxwell proceeded to calculate the speed of those waves, which of course depended on the numbers that came from lab experiments with electricity and magnetism (not with light!). He got the answer 310,740,000 meters per second. Maxwell must have had an "aha moment" when he recognized that number. He did recognize that number: it was the speed of light! He was lecturing at King's College, London, in 1862, and there he presented his result that the speed of propagation of an electromagnetic field is approximately that of the speed of light. He considered this to be more than just a coincidence, and commented: "We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."

He published his work in his 1864 paper, *A dynamical theory of the electromagnetic field*. He stated his important conclusion this way:

The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.

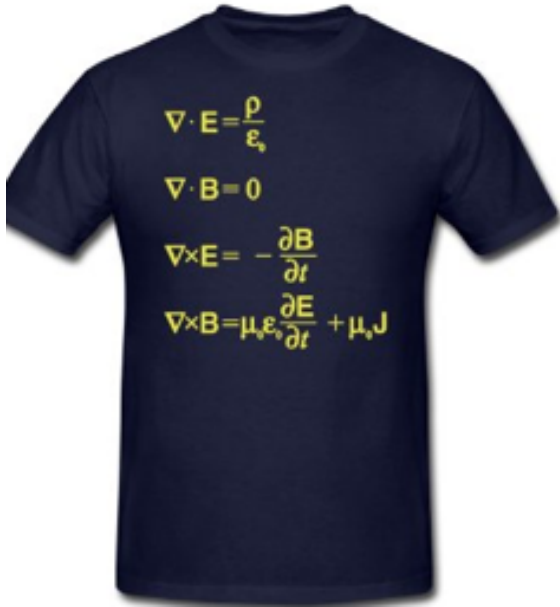
His famous equations, in their modern form of four partial differential equations, first appeared in fully developed form in his textbook, *A Treatise on Electricity and Magnetism* in 1873. That book is freely available on Google Scholar, at least through university libraries, so with a few clicks you can look at it yourself, especially Chapter XX, *Electromagnetic Theory of Light*. There you can see that Maxwell believed there must be an “electromagnetic medium” that vibrated, and carried the energy of the light from the source to the destination. It was already known that light has some wave-like properties (e.g. diffraction), so Maxwell thought that he had shown that the “luminiferous medium” (that carried light waves) was identical with the “electromagnetic medium.” It was another half-century before these ideas were both displaced by the quantum theory of light.

The world did not quite know what to make of Maxwell’s calculation. What did it mean? What were the further implications? Twenty years went by before the next major development—the discovery of radio waves by Hertz. Only then did technology follow Maxwell’s theoretical lead.

Maxwell was a devout Christian and was, according to the Wikipedia article and book it references for this claim, disappointed to see the theory of evolution making converts. He died of abdominal cancer at the age of 48. His mother had died of that same disease at the same age, when Maxwell was only 8.

As it turns out, this discovery was not such a complete surprise as it seems. Let’s look at some historical details (from the Wikipedia article on the speed of light’s historical section). There had been, ever since the time of the ancient Greeks, a controversy over whether the speed of light is finite or infinite. This was settled in the time of Galileo by Romer, who measured the periods of Io and other moons of Jupiter. Those periods were shorter when the Earth was closer to Jupiter, and in 1676 Romer used these measurements to calculate the speed of light that would be required to account for these changes in the measured orbital periods. Thus from 1676 on, the speed of light was known to be finite, but very fast. A better value had been obtained in the 19th century by Fizeau. The first connection to electromagnetism was *not* Maxwell’s prediction of waves, but eight years earlier, in 1856, when Wilhelm Eduard Weber and Rudolf Kohlrausch measured the ratio of the electromagnetic and electrostatic units of charge, $1/\sqrt{\epsilon_0\mu_0}$, by discharging a Leyden jar, and found that its numerical value was very close to the speed of light as measured by Fizeau. In 1862, just about when Maxwell was lecturing at King’s College, Lon Foucault who obtained a value of 298,000 km/s for the speed of light; Fizeau’s value was 315,000 km/s. The value that Maxwell calculated was somewhere in between the two.

Today, Maxwell's equations are so well-known that they decorate T-shirts:



I will now explain these equations as much as can be done without mathematics. Think of $\nabla \cdot$ as “flow of”; think of E as “electricity” and B as “magnetism”. Here “electricity” is a number, varying from point to point in space and also in time.

The first equation says that the flow of electricity away from a given point is determined by the charge density ρ near that point. “Charge” is not the same as “electricity”; charge is a source of electricity. The second equation says there’s nothing analogous to charge for magnetism. These two are known as Gauss’s laws.

Think of $\nabla \times$ as “flow around”, or “circulation of”. The third equation tells us what determines the circulation of electricity: changing magnetism, because that is what the term $\partial B/\partial t$ on the right means. This is “Faraday’s law of induction.” Maxwell did not invent this either; it dates back to 1831.

The last equation tells us what determines the circulation of magnetism: J is the electrical current (i.e. movement of charges), and $\partial E/\partial t$ is changing electricity (which is different from moving charges). Maxwell’s main contribution is the last term; without it, the equation is Ampere’s law, that electrical current produces magnetism. Maxwell realized that changing electricity also produces magnetism, and added that term.

These equations, with Maxwell’s new term, allow for wave-like solutions with no charges whatever; so J and ρ disappear, and E and B represent transverse waves; they have to be transverse to the direction of travel because $\nabla \times$ means “circulation of”. To verify this is easy, once you have studied vector calculus, which is the mathematics used to formulate the equations.