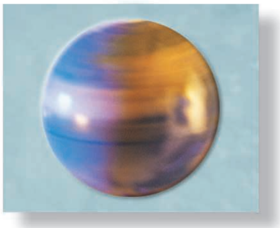
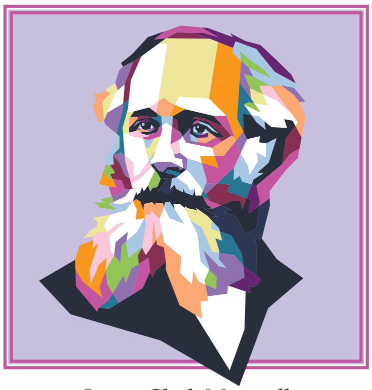


Around the Globe

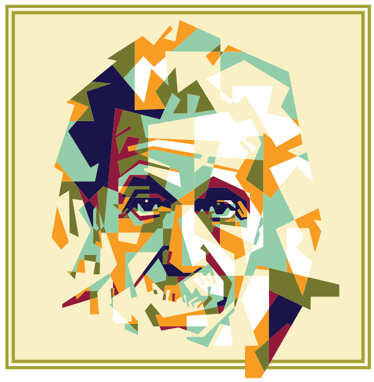
Maxwell, Einstein, Newton, and Faraday

■ **David O. Forfar**

When Einstein made his first visit to the United Kingdom, the press asked him if he had stood on the shoulders of Newton. Einstein replied, "That statement is not quite right. I stood on Maxwell's shoulders."

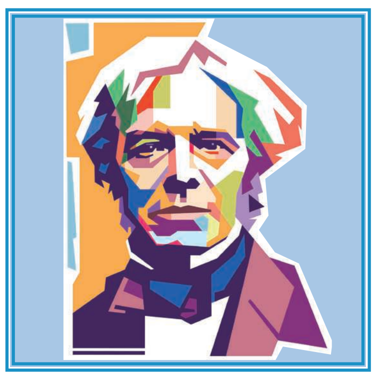


James Clerk Maxwell



Albert Einstein

Issac Newton



Michael Faraday

James Clerk Maxwell Foundation

This article is reprinted from the 2012 *Maxwell Newsletter*, with the permission of the James Clerk Maxwell Foundation (JCMF), which is dedicated to the life and history of Clerk Maxwell. A wealth of information is available at http://www.clerkmaxwellfoundation.org/. In addition, the JCMF owns and maintains an extensive collection of Maxwell material at his birthplace, 14 India Street, Edinburgh, Scotland. When travel conditions return to normal, visitors are most welcome. This article was arranged by David Forfar and James Rautio, both trustees of the JCMF.

David O. Forfar (doforfar@outlook.com) is a trustee and former chairman of the James Clerk Maxwell Foundation.

Digital Object Identifier 10.1109/MMM.2020.3014994
Date of current version: 6 October 2020

The late Cambridge professor, Stephen Hawking, Fellow of the Royal Society, stated in a television program some years ago that there was a story that Einstein had a picture of Clerk Maxwell, in addition to that of Faraday and Newton, on the wall of his Princeton study. The photograph of Einstein in his Princeton study (Figure 1) provides the proof for Maxwell, and we can also assume it was true for Newton and Faraday. Einstein's picture of Maxwell can be identified; it is a photograph of the portrait of Maxwell (Figure 2) by Lowes Dickinson that hangs in the hall of Trinity College, Cambridge.

In 1931, in an essay about Maxwell, Einstein wrote, "before Maxwell, physical reality was thought of as consisting of material particles. … Since Maxwell's time, physical reality has been thought of as represented by continuous fields. … This change in the conception of reality is the most profound and most fruitful that physics has experienced since the time of Newton."

Faraday and Maxwell saw electromagnetic fields, and their attendant taut "lines of force," as a means by which energy could be transmitted with a finite speed. The energy carried by certain fields, which warm any object in their path, is an example of the power of fields to transmit a physical effect (in this case, heat) across space.

Maxwell stated that it was Faraday (1791–1867) who, in 1846, first proposed that light was an electromagnetic wave. Faraday had recognized the ability of magnetism to alter light (its plane of polarization).

It was known that waves would travel through an elastic material at a speed equal to the square root of the ratio of its elastic modulus to its density. In his 1861 paper "On Physical Lines of Force," Maxwell assumed that electromagnetic waves traveled through such an "elastic material," called the *aether*. Maxwell estimated the aether's elastic modulus and density using known experimental results for the value of certain electrical and magnetic constants based on experiments that were nothing to do with light itself. The value of these electrical and magnetic constants had only been known since 1856, so Faraday himself was not able to estimate, in 1846, the speed of electromagnetic waves. However, in 1861, Maxwell was able to do so. This speed of these "electromagnetic" waves proved to be equal (within experimental error) to the known speed of light, derived by the French physicist Fizeau (1819–1896) from optical experiments on light itself. This so confirmed Faraday's prediction of 1846 that Maxwell was able to conclude in 1861, "... we can scarcely avoid the inference that light consists in the transverse undulations of the same medium, which is the cause of electric and magnetic phenomena."

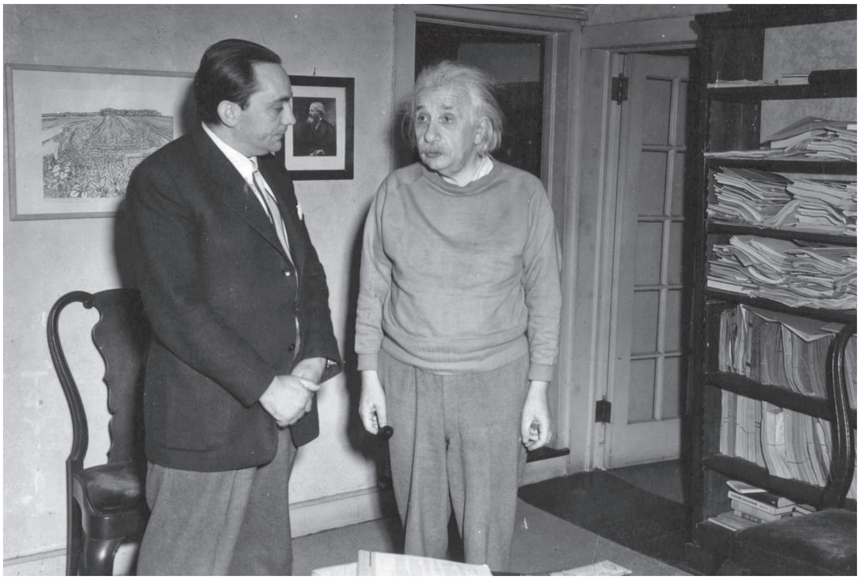


Figure 1. *Albert Einstein (right) in his Princeton study. His copy of Maxwell's portrait is visible above his right shoulder. (Source: Drew University and the Shelby White and Leon Levy Archives Center, Institute for Advanced Study, Princeton, New Jersey; used with permission.)*

Maxwell stated that it was Faraday who, in 1846, first proposed that light was an electromagnetic wave.

In 1865, in his paper "A Dynamical Theory of the Electromagnetic Field," Maxwell gave the equations governing all electric and magnetic phenomena. Certain of the equations were mathematical expressions of previous laws of electricity and magnetism, which had already been discovered by Coulomb, Ampère, Oersted, and Faraday.

In addition to these laws, Maxwell considered that a changing electric field would give rise to a special form of current. He used the analogy of positive and negative charges inside molecules (although these were then hardly known) being "displaced," i.e., being "pulled" in one direction and then "pushed" in the opposite direction (without the charges leaving the molecule), thereby creating a special type of current which needed to be included in the Oersted/Ampère law. This was new and innovative, and Maxwell used the name "displacement current," which we now know exists even in a vacuum. The equations governing the electromagnetic field are now known as *Maxwell's equations* and are among the most fundamental equations of physics, as they unify the electric and magnetic forces.

In 1864, Maxwell was then able to confirm, even more elegantly than he was able to do in his 1861 paper, that these equations lead to undulating, but mutually supportive, electric and magnetic fields. Maxwell showed again that the speed of these waves was, to within experimental error, equal to the known speed of light itself. Maxwell reiterated, "... it seems we have strong reason to conclude that light itself (including radiant heat and other radiations, if any) is an electromagnetic disturbance in the form of waves propagated … according the electromagnetic laws." This conclusion was the most stunning conclusion of 19th century theoretical physics, as many eminent physicists of the time did not believe in such electromagnetic waves traveling with finite speed (the speed of light), thinking instead that electric and magnetic effects were transmitted instantly across the universe ("action at a distance").

Some 22 years later, in 1887, when Maxwell, had he lived, would have been only 56, Hertz demonstrated, in the laboratory, such electromagnetic waves being transmitted and received and having all the properties—reflection, refraction, interference—of waves traveling at a finite speed. This was the most stunning conclusion of 19th century experimental physics.

Maxwell's own words, "including radiant heat and other radiations, if any," have proved prescient and have been amply vindicated by the progressive discovery of a whole spectrum of electromagnetic radiation of different wavelengths—radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays, and gamma rays. A telescope in Hawaii, named appropriately after James Clerk Maxwell, operates in the microwave part of the electromagnetic spectrum. Electromagnetic waves now provide the means for modern devices to communicate without wires, for example, today's mobile phones.

Maxwell's equations, without any alteration, were compatible with Einstein's special theory of relativity.

Einstein

Galileo and Newton had said that, in order to change (transform) between the viewpoints of two different observers

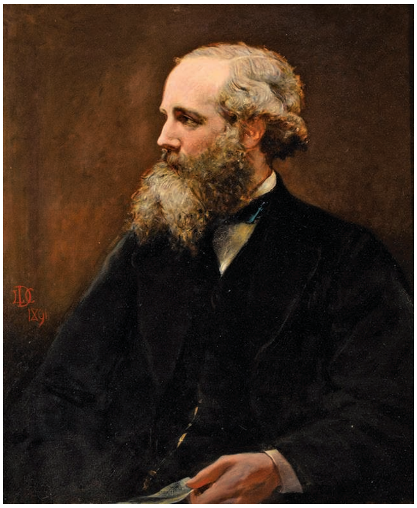


Figure 2. *Lowes Dickinson's portrait of Maxwell. (Source: The Master and Fellows, Trinity College, Cambridge; used with permission.)*

(viewing the same event but with one observer traveling with a constant speed and direction relative to the stationary observer), the speed of the moving observer would need to be added to the speed of the stationary observer. Thus, according to Galileo and Newton, "faster than light" speeds were perfectly possible. Maxwell's equations, on the other hand, gave an identical value for the speed of electromagnetic waves, no matter what the speed of the observer. These opposing theories could not both be right!

In his 1905 paper "On the Electrodynamics of Moving Bodies," Einstein derived the mathematical transformation (to change from one observer to another) that would result from the supposition that each observer, in his own frame of reference, measured an identical value for the speed of light. It turned out to be the same transformation which the physicist H. Lorentz (1853–1938) had formulated earlier.

In the same paper, Einstein showed his debt to Maxwell by demonstrating that Maxwell's equations, without any alteration, transformed correctly between two observers, provided the Lorentz transformation was used to change the viewpoint between the observers. It was such considerations that enabled Einstein to state confidently that nature behaved according to the Lorentz transformation and not according to the simpler Galileo/Newton transformation.

Maxwell's equations, without any alteration, were compatible with Einstein's special theory of relativity, whereas Newton's equations had to be changed. For example, the mass of a body now became dependent on its speed (as seen from Einstein's formula $m(v) = m/\sqrt{1 - v^2/c^2}$), whereas the mass of a body, under Newton, had always been a constant number, m, independent of the body's speed.

Furthermore, there could be no aether because, if there was such a thing, there would be a privileged observer in nature for whom the aether was at rest. Einstein told us that there are no privileged observers in inertial frames of reference.

Einstein further showed that, as a consequence of his 1905 paper, "if a body gives off energy L in the form of radiation, its mass diminishes by L/c^2." Einstein derived this formula by considering a body emitting an electromagnetic wave. The formula Einstein used for the energy of the resulting electromagnetic wave was the same one that Maxwell had derived. Einstein viewed the same event from the standpoint of both the stationary and the moving observer, using the Lorentz transform to change to the viewpoint from one observer to the other. By comparing the same *event*, as viewed from the two different viewpoints, he found the basis for his famous equation, $L = mc^2$ or, as we now say, $E = mc^2$.