A Brief History of Electromagnetism

Charles Byrne (Charles_Byrne@uml.edu)
Department of Mathematical Sciences
University of Massachusetts Lowell
Lowell, MA 01854, USA

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http://faculty.uml.edu/cbyrne/cbyrne.html)

January 2, 2015

Abstract

Understanding the connections between magnetism and electricity and exploiting that understanding for technological innovation dominated science in the nineteenth century, and yet no one saw it coming. In the index to Butterfield's classic history of the scientific revolution [3], which he locates roughly from 1300 to 1800, the word "electricity" does not appear.

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1 Who Knew?

These days, we tend to value science for helping us to predict things like hurricanes, and for providing new technology. The scientific activity we shall encounter in this brief history was not a quest for expanded powers and new devices, but a search for understanding; the expanded powers and new devices came later. The truly fundamental advances do not come from focusing on immediate applications, and, anyway, it is difficult to anticipate what applications will become important in the future. Nobody in 1960 thought that people would want a computer in their living room, just as nobody in 1990 wanted a telephone that took pictures.

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Electricity, as we now call it, was not completely unknown, of course. In the late sixteenth century, Gilbert, famous for his studies of magnetism, discovered that certain materials, mainly crystals, could be made attractive by rubbing them with a cloth. He called these materials *electrics*. Among Gilbert's accomplishments was his overturning of the conventional wisdom about magnets, when he showed, experimentally, that magnets *could* still attract nails after being rubbed with garlic. Sometime after Gilbert, electrostatic repulsion and induction were discovered, making the analogy with magnetism obvious. However, until some way was found to study electricity in the laboratory, the mysteries of electricity would remain hidden and its importance unappreciated.

2 "What's Past is Prologue"

The history of science is important not simply for its own sake, but as a bridge connecting the arts with the sciences. When we study the history of science, we begin to see science as an integral part of the broader quest by human beings to understand themselves and their world. Progress in science comes not only from finding answers to questions, but from learning to ask better questions. The questions we are able to ask, indeed the observations we are able to make, are conditioned by our society, our history, and our intellectual outlook. Science does not exist in a vacuum. As Shakespeare's line, carved into the wall of the National Archives building in Washington, D.C., suggests, the past sets the stage for what comes next, indeed, for what can come next.

3 Are We There Yet?

We should be careful when we talk about progress, either within science or more generally. Reasonable people can argue about whether or not the development of atomic weapons ought to be called progress. Einstein and others warned, at the beginning of the atomic age, that the emotional and psychological development of human beings had not kept pace with technological development, that we did not have the capacity to control our technology. It does seem that we have a difficult time concerning ourselves, as a society, with problems that will become more serious in the future, preferring instead the motto “I won’t be there. You won’t be there.”

We can certainly agree, though, that science, overall, has led us to a better, even if not complete, understanding of ourselves and our world and to the technology that is capable of providing decent life and health to far more people than in the past. These successes have given science and scientists a certain amount of political power that is not universally welcomed, however. Recent attempts to challenge the status of science within the community, most notably in the debate over creation “science” and evolution, have really been attempts to lessen the political power of science, not debates within science itself; the decades long attacks on science by the cigarette industry and efforts to weaken the EPA show clearly that it is not only some religious groups that want the political influence of science diminished.

Many of the issues our society will have to deal with in the near future, including nuclear power, terrorism, genetic engineering, energy, climate change, control of technology, space travel, and so on, involve science and demand a more sophisticated understanding of science on the part of the general public. The recent book *Physics for Future Presidents: the Science Behind the Headlines* [14] discusses many of these topics, supposedly as an attempt by the author to educate presidents-to-be, who will be called on to make decisions, to initiate legislation, and to guide the public debate concerning these issues.

History reminds us that progress need not be permanent. The technological expertise and artistic heights achieved by the Romans, even the mathematical sophistication of Archimedes, were essentially lost, at least in the west, for fifteen hundred years.

History also teaches us how unpredictable the future can be, which is, in fact, the underlying theme of this essay. No one in 1800 could have imagined the electrification that transformed society over the nineteenth century, just as no one in 1900 could have imagined Hiroshima and Nagasaki, only a few decades away, let alone the world of today.

4 Why Do Things Move?

In his famous "The Origins of Modern Science" [3] Butterfield singles out the problem of motion as the most significant intellectual hurdle the human mind has confronted and overcome in the last fifteen hundred years. The ancients had theories of motion, but for Aristotle, as a scientist perhaps more of a biologist than a physicist, motion as change in location was insignificant compared to motion as qualitative change, as, say, when an acorn grows into a tree. The change experienced by the acorn is clearly oriented toward a goal, to make a tree. By focusing on qualitative change, Aristotle placed too much emphasis on the importance of a goal. His idea that even physical motion was change toward a goal, that objects had a "natural" place to which they "sought" to return, infected science for almost two thousand years.

We must not be too quick to dismiss Aristotle's view, however. General relativity asserts that space-time is curved and that clocks slow down where gravity is stronger. Indeed, a clock on the top of the Empire State Building runs slightly faster than one at street level. As Brian Greene puts it,

Right now, according to these ideas, you are anchored to the floor because your body is trying to slide down an indentation in space (really, spacetime) caused by the earth. In a sense, all objects "want" to age as slowly as possible [9].

The one instance of motion as change in location whose importance the ancients appreciated was the motion of the heavens. Aristotle (384-322 B.C.) taught the geocentric theory that the heavens move around the earth. Aristarchus of Samos (310-230 B.C.) had a different view; according to Heath [10], "There is not the slightest doubt that Aristarchus was the first to put forward the heliocentric hypothesis." This probably explains why contemporaries felt that Aristarchus should be indicted for impiety. Ptolemy (100-170 A.D.) based his astronomical system of an earth-centered universe on the theories of Aristotle. Because the objects in the heavens, the moon, the planets and the stars, certainly appear to move rapidly, they must be made of an unearthly material, the *quintessence.*

The recent film "Agora" portrays the Alexandrian mathematician and philosopher Hypatia (350-415 A.D.) as an early version of Copernicus, but this is probably anachronistic. Her death at the hands of a Christian mob seems to have had more to do with rivalries among Christian leaders than with her scientific views and her belief in the heliocentric theory.

So things stood until the middle ages. In the fourteenth century the French theologian Nicole Oresme considered the possibility that the earth rotated daily around its own axis [12]. This hypothesis certainly simplified things considerably, and removed the need for the heavens to spin around the earth daily at enormous speeds. But even Oresme himself was hesitant to push this idea, since it conflicted with scripture.

Gradually, natural philosophers, the term used to describe scientists prior to the nineteenth century, began to take a more serious interest in motion as change in location, due, in part, to their growing interest in military matters and the trajectory of cannon balls. Now, motion on earth and motion of the heavenly bodies came to be studied by some of the same people, such as Galileo, and this set the stage for the unified theory of motion due to gravity that would come later, with Newton.

Copernicus' theory of a sun-centered astronomical system, Tycho Brahe's naked-eye observations of the heavens, Kepler's systematizing of planetary motion, the invention of the telescope and its use by Galileo to observe the pock-marked moon and the mini-planetary system of Jupiter, Galileo's study of balls rolling down inclined planes, and finally Newton's Law of Universal Gravitation marked a century of tremendous progress in the study of motion and put mechanics at the top of the list of scientific paradigms for the next century. Many of the theoretical developments of the eighteenth century involved the expansion of Newton's mechanics to ever more complex systems, so that, by the end of that century, celestial mechanics and potential theory were well developed mathematical subjects.

As we shall see, the early development of the field we now call electromagnetism involved little mathematics. As the subject evolved, the mathematics of potential theory, borrowed from the study of gravitation and celestial mechanics, was combined with the newly discovered vector calculus and the mathematical treatment of heat propagation to give the theoretical formulation of electromagnetism familiar to us today.

5 Go Fly a Kite!

The ancients knew about magnets and used them as compasses. Static electricity was easily observed and thought to be similar to magnetism. As had been known for centuries, static electricity exhibited both attraction and repulsion. For that reason, it was argued that there were two distinct types of electricity. Benjamin Franklin opposed this idea, insisting instead on two types of charge, positive and negative. Some progress was made in capturing electricity for study with the invention of the *Leyden jar*, a device for storing relatively large electrostatic charge (and giving rather large shocks). The discharge from the Leyden jar reminded Franklin of lightning and prompted him and others to fly kites in thunderstorms and to discover that lightning would charge a Leyden jar; lightning was electricity. These experiments led to his invention of the lightning rod, a conducting device attached to houses to direct lightning strikes down to the ground.

The obvious analogies with magnetism had been noticed by Gilbert and others in the late sixteenth century, and near the end of the eighteenth century Coulomb found that both magnetic and electrical attraction fell off as the square of the distance, as did gravity, according to Newton. Indeed, the physical connection between magnetism and gravity seemed more plausible than one between magnetism and electricity, and more worth studying. But things were about to change.

6 Bring in the Frogs!

In 1791 Galvani observed that a twitching of the muscles of a dead frog he was dissecting seemed to be caused by sparks from a nearby discharge of a Leyden jar. He noticed that the sparks need not actually touch the muscles, provided a metal scalpel touched the muscles at the time of discharge. He also saw twitching muscles when the frog was suspended by brass hooks on an iron railing in a thunderstorm. Eventually, he realized that the Leyden jar and thunderstorm played no essential roles; two scalpels of different metals touching the muscles were sufficient to produce the twitching. Galvani concluded that the electricity was in the muscles; it was *animal electricity.*

Believing that the electricity could be within the animals is not as far-fetched as it may sound. It was known at the time that there were certain “electric” fish that generated their own electricity and used it to attack their prey. When these animals were dissected, it was noticed that there were unusual structures within their bodies that other fish did not have. Later, it became clear that these structures were essentially batteries.

7 Lose the Frogs!

In 1800 Volta discovered that electricity could be produced by two dissimilar metals, copper and zinc, say, in salt water; no animal electricity here, and no further need for the frogs. He had discovered the *battery* and introduced *electrodynamics.* His primitive batteries, eventually called *voltaic piles*, closely resembled the electricity-producing structures found within the bodies of “electric” fish. Only six weeks after

Volta's initial report, Nicholson and Carlisle discovered *electrolysis*, the loosening up and separating of distinct atoms in molecules, such as the hydrogen and oxygen atoms in water.

The fact that chemical reactions produced electric currents suggested the reverse, that electrical currents could stimulate chemical reactions; this is *electrochemistry*, which led to the discovery and isolation of many new elements in the decades that followed. In 1807 Humphry Davy isolated some active metals from their liquid compounds and became the first to form sodium, potassium, calcium, strontium, barium, and magnesium.

In 1821 Seebeck found that the electric current would continue as long as the temperatures of the two metals were kept different; this is *thermoelectricity* and provides the basis for the *thermocouple*, which could then be used as a thermometer.

8 It's a Magnet!

In 1819 Oersted placed a current-carrying wire over a compass, not expecting anything in particular to happen. The needle turned violently perpendicular to the axis of the wire. When Oersted reversed the direction of the current, the needle jerked around 180 degrees. This meant that magnetism and electricity were not just analogous, but intimately related; *electromagnetism* was born. Soon after, Arago demonstrated that a wire carrying an electric current behaved like a magnet. Ampere, in 1820, confirmed that a wire carrying a current *was* a magnet by demonstrating attraction and repulsion between two separate current-carrying wires. He also experimented with wires in various configurations and related the strength of the magnetic force to the strength of the current in the wire. This connection between electric current and magnetism led fairly soon after to the telegraph, and later in the century, to the telephone.

9 A New World

Electric currents produce magnetism. But can magnets produce electric currents? Can the relationship be reversed? In 1831, Michael Faraday tried to see if a current would be produced in a wire if it was placed in a magnetic field created by another current-carrying wire. The experiment failed, sort of. When the current was turned on in the second wire, generating the magnetic field, the first wire experienced a brief current, but then nothing; when the current was turned off, again a brief current in the first wire. Faraday, an experimental genius who, as a young man, had been an assistant to Davy, and later the inventor of the refrigerator, made the right conjecture that it is not the mere presence of the magnetic field that causes a current, but changes in that magnetic field. He confirmed this conjecture by showing that a current would flow through a coiled wire when a magnetized rod was moved in and out of the coil; he (and, independently, Henry in the United States) had invented *electromagnetic induction* and the *electric generator* and, like Columbus, had discovered a new world.

10 Do The Math!

Mathematics has yet to appear in our brief history of electromagnetism, but that was about to change. Although Faraday, often described as being innocent of mathematics, developed his concept of *lines of force* in what we would view as an unsophisticated manner, he was a great scientist and his intuition would prove to be remarkably accurate.

In the summer of 1831, the same summer in which the forty-year old Faraday first observed the phenomenon of electromagnetic induction, the creation of an electric current by a changing magnetic field, James Clerk Maxwell was born in Edinburgh, Scotland.

Maxwell's first paper on electromagnetism, "On Faraday's Lines of Force" , appeared in 1855, when he was about 25 years old. The paper involved a mathematical development of the results of Faraday and others and established the mathematical methods Maxwell would use later in his more famous work "On Physical Lines of Force" .

Although Maxwell did not have available all of the compact vector notation we have today, his work was mathematically difficult. The following is an excerpt from a letter Faraday himself sent to Maxwell concerning this point.

There is one thing I would be glad to ask you. When a mathematician engaged in investigating physical actions and results has arrived at his conclusions, may they not be expressed in common language as fully, clearly and definitely as in mathematical formulae? If so, would it not be a great boon to such as I to express them so? - translating them out of their hieroglyphics, that we may work upon them by experiment.
Hasn't every beginning student of vector calculus and electromagnetism wished that Maxwell and his followers had heeded Faraday's pleas?

As Zajonc relates in [18], reading Faraday, Maxwell was surprised to find a kindred soul, someone who thought mathematically, although he expressed himself in pictures.

Maxwell felt that Faraday's use of "lines of force" to coordinate the phenomena of electromagnetism showed him to be "a mathematician of a very high order" .

Maxwell reasoned that, since an electric current sets up a magnetic field, and a changing magnetic field creates an electrical field, there should be what we now call *electromagnetic waves*, as these two types of fields leap-frog across (empty?) space. These waves would obey partial differential equations, called *Maxwell's equations*, although their familiar form came later and is due to Heaviside [7].

Around 1800 William Herschel used a prism and a thermometer to measure the temperature of colored light. He discovered that red light was warmer than violet light at the other end of the visible spectrum. He also noticed that there was measurable warmth beyond red light, even though no visible light was present. He had discovered the infra-red part of the electromagnetic spectrum. Around the same time J. W. Ritter found that silver chloride reacted when exposed to violet light, as well as to whatever was present beyond the visible violet light; he had discovered ultra-violet light. In 1819 David Brewster discovered that by putting a strain on some kinds of glass one could make the glass polarize light. Faraday, believing that everything was connected, somehow, wondered if light might also be affected by electricity. His experiments with electricity failed, so he turned to magnetism. In 1845 he discovered the Faraday effect, or the magneto-optical effect, that the plane of polarization of light could be modified by a nearby magnetic field.

Encouraged by these findings, Maxwell analyzed the mathematical properties of electromagnetic waves and discovered that the propagation speed of these waves was the same as that of light, leading to the conclusion that light itself is an electromagnetic phenomenon, distinguished from other electromagnetic radiation only by its frequency. That light also exhibits behavior more particle-like than wave-like is part of the story of the science of the 20th century.

Maxwell predicted that electromagnetic radiation could exist at various frequencies, not only those associated with visible light. Infrared and ultraviolet radiation had been known since early in the century, and perhaps they too were part of a *spectrum* of electromagnetic radiation. After Maxwell's death from cancer at forty-eight, Hertz demonstrated, in 1888, the possibility of electromagnetic radiation at very low frequencies, *radio waves.* In 1895 Röntgen discovered electromagnetic waves at the high-frequency end of the spectrum, the so-called *x-rays.*

11 Just Dot the i's and Cross the t's?

By the end of the nineteenth century, some scientists felt that all that was left to do in physics was to dot the i's and cross the t's. However, others saw paradoxes and worried that there were problems yet to be solved; how serious these might turn out to be was not always clear.

Maxwell himself had noted, about 1869, that his work on the specific heats of gases revealed conflicts between rigorous theory and experimental findings that he was unable to explain; it seemed that internal vibration of atoms was being "frozen out"at sufficiently low temperatures, something for which classical physics could not account. His was probably the first suggestion that classical physics could be "wrong". There were also the mysteries, observed by Newton, associated with the partial reflection of light by thick glass. Advances in geology and biology had suggested strongly that the earth and the sun were much older than previously thought, which was not possible, according to the physics of the day; unless a new form of energy was operating, the sun would have burned out a long time ago.

Newton thought that light was a stream of particles. Others at the time, notably Robert Hooke and Christiaan Huygens, felt that light was a wave phenomenon. Both sides were hindered by a lack of a proper scientific vocabulary to express their views. Around 1800 Young demonstrated that a beam of light displayed interference effects similar to water waves. Eventually, his work convinced people that Newton had been wrong on this point and most accepted that light is a wave phenomenon. Faraday, Maxwell, Hertz and others further developed the wave theory of light and related light to other forms of electromagnetic radiation.

In 1887 Hertz discovered the *photo-electric effect*, later offered by Einstein as confirming evidence that light has a particle nature. When light strikes a metal, it can cause the metal to release an electrically charged particle, an electron. If light were simply a wave, there would not be enough energy in the small part of the wave that hits the metal to displace the electron; in 1905 Einstein will argue that light is *quantized*, that is, it consists of individual bundles or particles, later called *photons*, each with enough energy to cause the electron to be released.

It was recognized that there were other problems with the wave theory of light. All known waves required a medium in which to propagate. Sound cannot propagate in a vacuum; it needs air or water or something. The sound waves are actually compressions and rarefactions of the medium, and how fast the waves propagate depends on how fast the material in the medium can perform these movements;

sound travels faster in water than in air, for example.

Light travels extremely fast, but does not propagate instantaneously, as Olaus Roemer first demonstrated around 1700. He observed that the eclipses of the moons of Jupiter appeared to happen sooner when Jupiter was moving closer to Earth, and later when it was moving away. He reasoned, correctly, that the light takes a finite amount of time to travel from the moons to Earth, and when Jupiter is moving away the distance is growing longer.

If light travels through a medium, which scientists called the *ether*, then the ether must be a very strange substance indeed. The material that makes up the ether must be able to compress and expand very quickly. Light comes to us from great distances so the ether must extend throughout all of space. The earth moves around the sun, and therefore through this ether, at a great speed, and yet there are no friction effects, while very much slower winds produce a great deal of weathering. Light can also be polarized, so the medium must be capable of supporting transverse waves, not just longitudinal waves, as in acoustics. To top it all off, the Michelson-Morley experiment, performed in Cleveland in 1887, failed to detect the presence of the ether. The notion that there is a physical medium that supports the propagation of light would not go away, however. Late in his long life Lord Kelvin (William Thomson) wrote “One word characterizes the most strenuous efforts ... that I have made perseveringly during fifty-five years: that word is FAILURE.” Thomson refused to give up his efforts to combine the mathematics of electromagnetism with the mechanical picture of the world.

12 Seeing is Believing

If radio waves can travel through an invisible ether, and if hypnotists can *mesmerize* their subjects, why can’t human beings communicate telepathically with each other and with the dead? Why should atoms exist when we cannot see them, while ghosts must not, even when, as some claimed, they have shown up in photographs? When is seeing believing?

In the late 1800’s the experimental physicist William Crooke claimed to have discovered *radiant matter* [5]. When he passed an electric current through a glass tube filled with a low-pressure gas, a small object within the tube could be made to move from one end to the other, driven, so Crooke claimed, by radiant particles of matter, later called *cathode rays*, streaming from one end of the tube to the other. Crooke then went on, without much success, to find material explanation for some of the alleged effects of spiritualism. He felt that it ought to be possible for humans to receive transmissions in much the same way as a radio receives signals. It was a time of considerable uncertainty, and it was not clear that Crooke's radiant matter, atoms, x-rays, radio waves, radioactivity, and the ether were any more real than ghosts, table tapping, and communicating with the dead; they all called into question established physics.

Crooke felt that scientists had a calling to investigate all these mysteries, and should avoid preconceptions about what was true or false. Others accused him of betraying his scientific calling and of being duped by spiritualists. Perhaps remembering that even the word "scientist" was unknown prior to the 1830's, they knew, nevertheless, that, if the history of the nineteenth century taught them anything, it was that there were also serious problems on the horizon of which they were completely unaware.

13 If You Can Spray Them, They Exist

Up through the seventeenth century, philosophy, especially the works of Aristotle, had colored the way scientists looked at the physical world. By the end of the nineteenth century, most scientists would have agreed that philosophy had been banished from science, that statements that could not be empirically verified, that is, metaphysics, had no place in science. But philosophy began to sneak back in, as questions about causality and the existence of objects we cannot see, such as atoms, started to be asked [1]. Most scientists are probably *realists*, believing that the objects they study have an existence independent of the instruments used to probe them. On the other side of the debate, *positivists*, or, at least, the more extreme positivists, hold that we have no way of observing an observer-independent reality, and therefore cannot verify that there is such a reality. Positivists hold that scientific theories are simply instruments used to hold together observed facts and make predictions. They do accept that the theories describe an *empirical* reality that is the same for all observers, but not a reality independent of observation. At first, scientists felt that it was safe for them to carry on without worrying too much about these philosophical points, but quantum theory would change things [11].

The idea that matter is composed of very small indivisible *atoms* goes back to the ancient Greek thinkers Democritus and Epicurus. The philosophy of Epicurus was popularized during Roman times by Lucretius, in his lengthy poem *De Rerum Natura* ("On the Nature of Things"), but this work was lost to history for almost a thousand years. The discovery, in 1417, of a medieval copy of the poem changed the course of history, according to the author Stephen Greenblatt [8]. Copies of the poem became widely distributed throughout Europe and eventually influenced the thinking of Galileo, Freud, Darwin, Einstein, Thomas Jefferson, and many others. But it wasn't until after Einstein's 1905 paper on Brownian motion and subsequent experimental confirmations of his predictions that the actual existence of atoms was more or less universally accepted.

I recall reading somewhere about a conversation between a philosopher of science and an experimental physicist, in which the physicist was explaining how he sprayed an object with positrons. The philosopher then asked him if he really believed that positrons exist. The physicist answered, "If you can spray them, they exist."

14 What's Going On Here?

Experiments with cathode rays revealed that they were deflected by magnets, unlike any form of radiation similar to light, and unresponsive to gravity. Maybe they were very small electrically charged particles. In 1897 J.J. Thomson established that the cathode rays were, indeed, electrically charged particles, which he called *electrons*. For this discovery he was awarded the Nobel Prize in Physics in 1906. Perhaps there were two fundamental objects in nature, the atoms of materials and the electrons. However, Volta's experiments suggested the electrons were within the materials and involved in chemical reactions. In 1899 Thomson investigated the photo-electric effect and found that cathode rays could be produced by shining light on certain metals; the photo-electric effect revealed that electrons were inside the materials. Were they between the atoms, or inside the atoms? If they were within the atoms, perhaps their number and configuration could help explain Mendeleev's periodic table and the variety of elements found in nature.

In 1912, Max von Laue demonstrated that Röntgen's x-ray beams can be diffracted; this provided a powerful tool for determining the structure of crystals and molecules and later played an important role in the discovery of the double-helix structure of DNA. In 1923, the French physicist Louis de Broglie suggested that moving particles, such as electrons, should exhibit wave-like properties characterized by a wave-length. In particular, he suggested that beams of electrons sent through a narrow aperture could be diffracted. In 1937 G.P. Thomson, the son of J.J. Thomson, shared the Nobel Prize in Physics with Clinton Davisson for their work demonstrating that beams of electrons can be diffracted. As someone once put it, "The father won the prize for showing that electrons are particles, and the son won it for showing that they aren't." Some suggested that, since beams of electrons exhibited wave-like properties, they should give rise to the sort of interference effects Young had shown were exhibited by beams of light. The first laboratory experiment showing double-slit interference effects of beams of electrons was performed in 1989.

J.J. Thomson also discovered that the kinetic energy of the emitted electrons depended not at all on the intensity of the light, but only on its frequency. This puzzling aspect of the photo-electric effect prompted Einstein to consider the possibility that light is quantized, that is, it comes in small "packages", or *light quanta*, later called *photons*. Einstein proposed quantization of light energy in his 1905 work on the photo-electric effect. It was this work, not his theories of special and general relativity, that eventually won for Einstein the 1921 Nobel Prize in Physics.

Einstein's 1905 paper that deals with the photo-electric effect is really a paper about the particle nature of light. But this idea met with great resistance, and it was made clear to Einstein that his prize was not for the whole paper, but for that part dealing with the photo-electric effect. He was even asked not to mention the particle nature of light in his Nobel speech.

Around 1900 Max Planck had introduced quantization in his derivation of the energy distribution as a function of frequency in black-body radiation. Scholars have suggested that he did this simply for computational convenience, and did not intend, at that moment, to abandon classical physics. Somewhat later Plank and others proposed that the energy might need to be quantized, in order to explain the absence of what Ehrenfest called the *ultraviolet catastrophe* in black-body radiation.

Were the electrons the only sub-atomic particles? No, as Rutherford's discovery of the atomic nucleus in 1911 would reveal. And what is radioactivity, anyway? The new century was dawning, and all these questions were in the air. It was about 1900, Planck had just discovered the quantum theory, Einstein was in the patent office, where he would remain until 1909, Bohr and Schrödinger schoolboys, Heisenberg not yet born. A new scientific revolution was about to occur, and, as in 1800, nobody could have guessed what was coming next [13].

15 The Year of the Golden Eggs

As Rigden relates in [15], toward the end of his life Einstein looked back to 1905, when he was twenty-six, and told Leo Szilard, "They were the happiest years of my life. Nobody expected me to lay golden eggs." It is appropriate to end our story in

1905 because it was both an end and a beginning. In five great papers published in that year, Einstein solved several of the major outstanding problems that had worried physicists for years, but the way he answered them was revolutionary and began a whole new era of physics. After 1905 the development of electromagnetism merges with that of quantum mechanics, and becomes too big a story to relate here.

The problems that attracted Einstein involved apparent contradictions, and his answers were surprising. Is matter continuous or discrete? It is discrete; atoms do exist. Is light wave-like or particle-like? It is both. Are the laws of thermodynamics absolute or statistical? They are statistical. Are the laws of physics the same for observers moving with uniform velocity relative to one another? Yes; in particular, each will measure the speed of light to be the same. And, by the way, our notion of three-dimensional space and a separate dimension of time is wrong (special relativity), and gravity and acceleration are really the same thing (general relativity). Is inertial mass the same as gravitational mass? Yes. And what is mass, anyway? It is really energy, as $E = mc^2$ tells us.

16 Do Individuals Matter?

Our brief history of electromagnetism has focused on a handful of extraordinary people. But how important are individuals in the development of science, or in the course of history generally? An ongoing debate among those who study history is over the role of the Great Man [4]. On one side of the debate is the British writer and hero-worshipper Carlyle: “Universal history, the history of what man has accomplished in this world, is at bottom the History of the Great Men who have worked here.” On the other side is the German political leader Bismarck: “The statesman’s task is to hear God’s footsteps marching through history, and to try to catch on to His coattails as He marches past.”

If Mozart had never lived, nobody else would have composed his music. If Picasso had never lived, nobody else would have painted his pictures. If Winston Churchill had never lived, or had he died of his injuries when, in 1930, he was hit by a car on Fifth Avenue in New York City, western Europe would probably be different today. If Hitler had died in 1930, when the car he was riding in was hit by a truck, recent history would certainly be different, in ways hard for us to imagine. But, I think the jury is still out on this debate, at least as it applies to science.

I recently came across the following, which I think makes this point well. Suppose that you were forced to decide which one of these four things to“consign to oblivion” , that is, make it never to have happened: Mozart's opera *Don Giovanni*, Chaucer's *Canterbury Tales*, Newton's *Principia*, or Eiffel's tower. Which one would you choose? The answer has to be Newton's *Principia*; it is the only one of the four that is not irreplaceable.

If Newton had never lived, we would still have Leibniz's calculus. Newton's Law of Universal Gravitation would have been discovered by someone else. If Faraday had never lived, we would still have Henry's discovery of electromagnetic induction. If Darwin had never lived, someone else would have published roughly the same ideas, at about the same time; in fact, Alfred Russel Wallace did just that. If Einstein had not lived, somebody else, maybe Poincaré, would have hit on roughly the same ideas, perhaps a bit later. Relativity would have been discovered by someone else. The fact that light behaves both like a wave and like a particle would have become apparent to someone else. The fact that atoms do really exist would have been demonstrated by someone else, although perhaps in a different way.

Nevertheless, just as Mozart's work is unique, even though it was obviously influenced by the times in which he composed and is clearly in the style of the late 18th century, Darwin's view of what he was doing differed somewhat from the view taken by Wallace, and Einstein's work reflected his own fascination with apparent contradiction and a remarkable ability, "to think outside the box" , as the currently popular expression has it. Each of the people we have encountered in this brief history made a unique contribution, even though, had they not lived, others would probably have made their discoveries, one way or another.

People matter in another way, as well. Science is the work of individual people just as art, music and politics are. The book of nature, as some call it, is not easily read. Science is a human activity. Scientists are often mistaken and blind to what their training and culture prevent them from seeing. The history of the development of science is, like all history, our own story.

17 What's Next?

The twentieth century has taught us that all natural phenomena are based on two physical principles, quantum mechanics and relativity. The combination of special relativity and quantum mechanics led to a unification of three of the four fundamental forces of nature, electromagnetic force and the weak and strong nuclear forces, originally thought to be unrelated. The remaining quest is to combine quantum mechanics with general relativity, which describes gravity. Such a unification seems necessary if one is to solve the mysteries posed by *dark matter* and *dark energy* [2], which make up most of the *stuff* of the universe, but of which nothing is known and whose existence can only be inferred from their gravitational effects. Perhaps what will be needed is a *paradigm shift*, to use Kuhn's popular phrase; perhaps the notion of a *fundamental particle*, or even of an *observer*, will need to be abandoned.

The June 2010 issue of *Scientific American* contains an article called "Twelve events that will change everything". The article identifies twelve events, both natural and man-made, that could happen at any time and would transform society. It also rates the events in terms of how likely they are to occur: fusion energy (very unlikely); extraterrestrial intelligence, nuclear exchange, and asteroid collision (unlikely); deadly pandemic, room-temperature superconductors, and extra dimensions (50-50); cloning of a human, machine self-awareness, and polar meltdown (likely); and creation of life, and Pacific earthquake (almost certain). Our brief study of the history of electromagnetism should convince us that the event that will *really* change everything is not on this list nor on anyone else's list. As Brian Greene suggests [9], people in the year 2100 may look back on today as the time when the first primitive notions of parallel universes began to take shape.

18 Unreasonable Effectiveness

As Butterfield points out in [3], science became modern in the period 1300 to 1800 not when experiment and observation replaced adherence to the authority of ancient philosophers, but when the experimentation was performed under the control of mathematics. New mathematical tools, logarithms, algebra, analytic geometry, and calculus, certainly played an important role, but so did mathematical thinking, measuring quantities, rather than speculating about qualities, idealizing and abstracting from a physical situation, and the like. Astronomy and mechanics were the first to benefit from this new approach. Paradoxically, our understanding of electromagnetism rests largely on a century or more of intuition, conjecture, experimentation and invention that was almost completely free of mathematics. To a degree, this was because the objects of interest, magnets and electricity, were close at hand and, increasingly, available for study. In contrast, Newton's synthesis of terrestrial and celestial gravitation was necessarily largely a mathematical achievement; observational data was available, but experimentation was not possible.

With Maxwell and the mathematicians, electromagnetism became a modern science. Now electromagnetism could be studied with a pencil and paper, as well as with generators. Consequences of the equations could be tested in the laboratory and used to advance technology. The incompleteness of the theory, with regard to the ether, the arrow of time, the finite speed of light, also served to motivate further theoretical and experimental investigation.

As electromagnetism, in particular, and physics, generally, became more mathematical, studies of the very small (nuclear physics), the very large (the universe), and the very long ago (cosmology) became possible. The search for unifying theories of everything became mathematical studies, the consequences of the theories largely beyond observation [16].

One of the great mysteries of science is what the physicist Eugene Wigner called "the unreasonable effectiveness of mathematics". Maxwell's mathematics suggested to him that visible light was an electromagnetic phenomenon, occupying only a small part of an electromagnetic spectrum, and to Hertz that there might be radio waves. Dirac's mathematics suggested to him the existence of anti-matter, positrons with the mass of an electron, but with a positive charge, and with the bizarre property that, when a positron hits an electron, their masses disappear, leaving only energy. What was fantastic science fiction in 1930 is commonplace today, as anyone who has had a positron-emission-tomography (PET) scan is well aware. Mathematics pointed to the existence of the Higgs boson, recently discovered at CERN.

In 2000 the mathematical physicist Ed Witten wrote a paper describing the physics of the century just ending [17]. Even the title is revealing; the quest is for *mathematical* understanding. He points out that, as physics became more mathematical in the first half of the twentieth century, with relativity and non-relativistic quantum mechanics, it had a broad influence on mathematics itself. The equations involved were familiar to the mathematicians of the day, even if the applications were not, and their use in physics prompted further mathematical development, and the emergence of new fields, such as functional analysis. In contrast, the physics of the second half of the century involves mathematics, principally quantum concepts applied to fields, not just particles, the foundations of which are not well understood by mathematicians. This is mathematics with which even the mathematicians are not familiar. Providing a mathematical foundation for the standard model for particle physics should keep the mathematicians of the next century busy for a while. The most interesting sentence in [17] is *The quest to understand string theory may well prove to be a central theme in physics of the twenty-first century.* Are physicists now just trying to understand their own mathematics, instead of the physical world?

19 Coming Full Circle

As we have seen, prior to Maxwell, electromagnetism was an experimental science. With the coming of quantum mechanics, it became a mathematical study. Advances came from equations like Dirac's, more than from laboratories.

Within the last couple of decades, however, the circle has begun to close. As scientists began to use computers to study their equations, strange phenomena began to emerge: sensitive dependence on initial conditions in the equations used to study the weather; chaotic behavior of sequences of numbers generated by apparently simple formulas; fractal images appearing when these simple formulas were displayed graphically. At first, it was thought that the strange behavior was coming from numerical errors, but soon similar behavior was observed in natural systems. Chaos theory, complexity and the study of emergent phenomena are the products of computer-driven experimental mathematics.

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