The *aurora australis* photographed from the International Space Station. Image credit: NASA
On May 29, 2010, looking southward from a vantage point about 350 kilometers above the southern Indian Ocean, astronauts onboard the International Space Station watched this enormous, green ribbon shimmering below. Known as aurora australis, or southern lights, the shifting, luminous bands are commonly seen at high northern latitudes as well, where they are known as the aurora borealis, or northern lights. North or south, their cause is the same though, as energetic charged particles from the magnetosphere pile into the atmosphere near the Earth's poles. To produce the characteristic greenish glow, the energetic particles excite oxygen atoms at altitudes of 100 kilometers or more. Aurora on May 24 were likely triggered by the interaction of the magnetosphere with a coronal mass ejection erupting from the Sun on May 24.

From the Editor:
In this issue of Phys13news we explore some of the rich history of the development of our understanding of electricity and magnetism, focusing on the human side of scientific discovery. The five articles are based on essays submitted by physics students at Waterloo as part of their fourth-year electromagnetism course. We begin with Coulomb and his little-known background in engineering and the science of friction, and the eventual discovery of his celebrated inverse-square force law of electrostatics. We then turn to Ampère: his troubled life, his philosophy, and his unique approach to science, culminating in his discovery of the nature of the magnetostatic force between two current-carrying wires (which was later explained in terms of the Biot-Savart law combined with the Lorentz force law). The great Michael Faraday (who will be discussed in a future issue) was instrumental in introducing the modern concept of electric and magnetic fields (his “lines of force”), which was subsequently given a full mathematical description by James Clerk Maxwell. Our third and fourth articles are devoted to Maxwell. The first of these focusses on Maxwell’s accomplishments outside of electromagnetism—in particular his fascinating work on Saturn’s rings and the kinetic theory of gasses, and why he is considered one of the greatest physicists of all time, alongside Newton and Einstein. The second article on Maxwell discusses how his ether-based theory of electromagnetism influenced Einstein’s development of Special Relativity. Note to teachers: This is a must-read if you are teaching Special Relativity, as it addresses several egregious and widespread misconceptions, e.g., that the Michelson-Morley experiment ruled out the ether—it did not! Our last article explores the life and work of Hertz, who played a crucial role in the experimental confirmation of Maxwell’s theory, paving the way for the wireless revolution of the 20th century and its immeasurable impact on technology and society. Enjoy!

—Richard Epp, Editor
**Charles-Augustin de Coulomb**

*Portrait of Charles-Augustin de Coulomb (1736-1806).*

By Jennifer Czekus

**INTRODUCTION**

We discuss the history of Charles-Augustin de Coulomb. First, his early life, education, and projects that influenced the discovery of Coulomb's law; second, the impact of this law on the physics community then and now, particularly its impact on later discoveries in electromagnetism.

**EARLY LIFE OF COULOMB**

Coulomb was a privileged child, born in Angouleme, France to two wealthy and respected parents on June 14, 1736. The success of his parents allowed him to experience a top education. His family moved to Paris where he attended the College Mazarin, where he received a thorough education in mathematics, astronomy, chemistry and botany. After a fight with his mother regarding career choices, he moved to Montpellier with his father, where in 1757 he joined the Society of Sciences because of his interests in mathematics and astronomy.

Coulomb’s interests later changed to engineering and in 1758 he returned to Paris with his mother to prepare for the entrance exams at the École du Génie at Mézières, which he entered in 1760.

During his studies, he formed important relationships with Charles Bossut (a mathematician and student of d’Alembert) and Jean Charles de Borda (known for the Borda repeating circle, and commemorated on the Eiffel tower).

In 1761, Coulomb graduated as a professional engineer and lieutenant in the Corps du Génie. He spent the next twenty years devoted to engineering in various places, working on structural design projects, fortifications, soil mechanics, and other areas. One project was to build the new Fort Bourbon, which would later contribute to his theoretical memoirs on mechanics. Another project in Martinique caused a health decline that would affect him for the rest of his life.

In 1773, he was sent to Bouchain where we began to write papers on applied mechanics. His mathematics background gave the basis for him to use calculus of variations to solve engineering problems rather than using numerical solutions. His work was valued for using sophisticated mathematics not typical in engineering then, and he was highly recognized by the Académie des Sciences.

After Bouchain, Coulomb was assigned to Cherbourg where he wrote a memoir on the magnetic compass, which included his first thoughts on a new torsion balance. He solved torsion problems in cylinders, developing theory using silk threads and hair. He showed how the torsion bar suspension could be used to measure extremely small forces, and paved the way for torsion balance applications for future physicists. He submitted this paper to the Grand Prix of the Académie des Sciences in 1777 which won him a share of the prize.

Coulomb also spent time at Rochefort where he researched mechanics and friction; the shipyards there were his laboratory. His theory involved static and dynamic friction of sliding surfaces, friction in bending cords, and friction in rolling. He developed a series of two-term equations—one term being a constant and a second depending on time, normal force, velocity, or another parameter. This work won him another Grand Prix from the Académie des Sciences in 1781.

Coulomb’s contributions to the study of friction led scientists to think of him as the creator of the science of friction.

**DISCOVERY OF COULOMB’S LAW**

After Coulomb’s great contributions to the science of friction, he was elected to the Académie des Sciences in Paris for a permanent post in the mechanics section. He gave up engineering projects and strictly pursued physics. Between 1785 and 1791, we wrote seven papers on electricity and magnetism and submitted them to the Académie des Sciences.

Following Newton’s law of gravitation and its inverse square law with respect to distance, scientists theorized that other natural phenomena may follow this inverse square law—including electricity.
Coulomb put these theories to the test experimentally.

He developed an apparatus to measure torsional balance that led to his discovery of Coulomb’s law (see drawing below). The hanging needle measures the forces without the disturbance of friction, and the two pith balls were charged. Once charged, they immediately repelled each other, and the repulsion was measured by turning the micrometer to force the balls closer together. Coulomb only reported three measurements:

1. Having electrified the two balls with the pinhead, the index of the micrometer pointing to 0, the ball ‘a’ on the needle is displaced from the ball ‘t’ by 36°.

2. Having twisted the suspended filament, by means of the knob ‘o’ of the micrometer to 126°, the two balls approached one another and stopped at 18° of distance of the one from the other.

3. Having twisted the suspended filament by 567°, the two balls approached another to 8 ½°.

**Coulomb put these theories to the test experimentally.**

**COULOMB’S TORSION BALANCE**

From these measurements, Coulomb concluded that these numbers showed that when the distance between the charged balls is halved, their force of repulsion is quadrupled, which implies an inverse-square force law.

Coulomb then explained his results algebraically, and consequently developed his eponymous Coulomb’s law:

\[ F = k \frac{q_1 q_2}{d^2} \]

**IMPACT OF COULOMB’S LAW ON LATER DISCOVERIES**

Coulomb’s law is one of the most fundamental equations in physics, influencing later major contributions to physics like Poisson’s mathematical theory of magnetic forces. During his time in Blois, he continued research in the attractive and repulsive forces between magnetic poles, which was the foundation for Poisson’s theory of magnetic forces.

**REFERENCES**


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**Puzzle Corner**

by Tony Anderson

**Linked Laureates #1: from A to Z**

The chain below combines together the surnames of eleven Nobel Laureates in Physics. The link between adjacent surnames is that the last letter of one is the first letter of the next. Each hyphen corresponds to one missing letter. As an additional aid for longer names, an extra lowercase letter is given. See how well you know your Laureates by filling in as many letters as possible!

A---r--N--L--B---G---r---e--h---S---k---Y---a---a---Z----N

The solution is given on page 16 of this issue.
Ampère had an interesting way of approaching science and it is this approach that led him to the aforementioned discovery. He was concerned with what could be known as fact; he disliked probabilities and uncertainty. His metaphysical philosophy was his top priority and only through careful analysis did he arrive at his great experimental result.

BACKGROUND INFORMATION
André-Marie Ampère was born on January 22, 1775 in Lyons, France and died June 10, 1836 in Marseilles, France. Ampère's father, Jean-Jacques Ampère was a prosperous merchant who believed and followed the teaching of Rousseau. In short, Rousseau believed that formal teaching was stifling for young boys and that instead, they should learn directly from nature. This philosophy laid the path that his son, André, was to follow. Ampère was self-taught, reading from his father's extensive book collection. One of the most influential readings that Ampère came across was that of Descartes. Descartes was convinced that he couldn't trust his senses and it is this thought, perhaps, that laid the foundation for Ampère's experimental work in physics. At an early age, he taught himself elements of number theory and learned from books written by Euclid. He even learned Latin so as to read the works of Euler and Bernoulli.

Ampère was a devout Catholic, and influenced by his mother, Jeanne Desutieres-Sarcey. At the age of fourteen, Ampère's life took a drastic downward turn. It was at the outbreak of the French Revolution when Ampère's father was enlisted as a "juge de paix." All was fine for awhile until, on November 23, 1793 Ampère's father was tried and killed when Lyons was defeated by the Republic. Ampère was devastated and devoted himself to the subject of botany. He met his future wife during this time and he wed Julie Carron on August 7, 1799. A son was born on August 12, 1800 and was named after his father, Jean-Jacques. Tragically, Julie fell ill after the birth of their son and died 4 years later. He married again August 1, 1806 to Jeanne Potot. This, however, was short-lived and after his father-in-law took most of his money, and his second child—a daughter, Albine, he divorced his wife. His daughter married a drunkard who worked as an army officer, and his son, despite great hopes, was a roamer in an entourage of a beautiful woman, Mme. Recamier. All the while Ampère took solace in his religion and looked with a fierce desire for something that was certain. This quest for certainty and truth ultimately was the basis for his scientific philosophy.

TEACHING APPOINTMENTS
After his first marriage, Ampère made a living as a mathematics teacher in Lyons. In 1802 he became a professor of physics and chemistry at the Ecole Centrale in Bourg-en-Bresse.
To make a reputation for himself, he wrote his first paper on probability theory called, "Considerations sur la théorie mathématique du jeu" [1]. France, at this time, was run by Napoleon who appointed Ampère to the newly made post of Inspector General in the newly-formed university system; he held this post until his death. After this, his career took a great leap and in 1814 he became a member of the class of mathematics at the Institut Imperial. In 1820 he became an assistant professor of astronomy at the University of Paris and, finally, in 1824 Ampère became the chair of experimental physics of the Collège de France.

PHILOSOPHY AND CONTRIBUTIONS

Ampère was interested in metaphysics and therefore he rejected the ideology of the majority of France whose philosophy left God and the existence of an objective world in incertitude. Ampère wanted certainty and an objective world including God. He was open minded and had no trouble adapting his world view based on new data. It is this open-mindedness that allowed Ampère to become the father of electrodynamics. It was during a meeting of the French Academy of Sciences, which Ampère attended, that François Arago reported Hans Oersted's discovery of electromagnetism in 1820. Coulomb had apparently shown in 1780 that electricity and magnetism had interactions, and although others were skeptical of these findings, Ampère accepted them immediately and within the month he reported to the Académie de Sciences three times about Ampère's memoir sum up his phenomenological electrodynamics achievements: [2]

1) Two electric currents attract one another when they move parallel to one another in the same direction; they repel one another when they move parallel but in opposite directions.

2) It follows that when the metallic wires through which they pass can turn only in parallel planes, each of the two currents tends to swing the other into a position parallel to it and pointing in the same direction.

3) These attractions and repulsions are absolutely different from the attractions and repulsions of static electricity.

4) All the phenomena presented by the mutual action of an electric current and a magnet discovered by H. Oersted are covered by the law of attraction and of repulsion of two electric currents that has just been enunciated, if one admits that a magnet is only a collection of electric currents produced by the action of the particles of steel upon one another analogous to that of the elements of a voltaic pile, and which exist in planes perpendicular to the line which joins the two poles of the magnet.

5) When a magnet is in the position that it tends to take by the action of the terrestrial globe, these currents move in a sense opposite to the apparent motion of the sun; when one places the magnet in the opposite position so that the poles directed towards the poles of the earth are the same [S to S and N to N, not south-seeking to S, etc.] the same currents are found in the same direction as the apparent motion of the sun.

6) The known observed effects of the action of two magnets on one another obey the same Law.

7) The same is true of the force that the terrestrial globe exerts on a magnet, if one admits electric currents in planes perpendicular to the direction of the declination needle, moving from east to west, above this direction.

8) There is nothing more in one pole of a magnet than in the other; the sole difference between them is that one is to the left and the other is to the right of the electric currents which give the magnetic properties to the steel.

9) Although Volta has proven that the two electricity, positive and negative, of the two ends of the pile attract and repel one another according to the same laws as the two electricity produced by means known before him, he has not by that demonstrated completely the identity of the fluids made manifest by the pile and by friction; this identity was proven, as much as a physical truth can be proven, when he showed that two bodies, one electrified by the contact of [two] metals, and the other by friction, acted upon each other in all circumstances as though both had been electrified by the pile or by the common electric machine [electrostatic generator]. The same kind of proof is applicable here to the identity of attractions and repulsions of electric currents and magnets.

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ABSTRACT

Maxwell’s equations are ubiquitous in their influence; and for good reason. Together with Lorentz’s force law, they are essential to the understanding of electrodynamics and other fields of physics. Yet these equations, of whose early form Maxwell published between 1861 and 1862, are only a small part of his life; what about the rest of it? Why is James Clerk Maxwell, born as John Clerk in 1831, so highly revered amongst physicists? It is worthwhile to explore his other accomplishments and the influences he had throughout his life. Here, we will briefly examine his personal life, and focus on the influences he has exerted on the people and science around him. Skirting around Maxwell’s equations in electromagnetism, we will also consider his influence on optics and thermodynamics.

INTRODUCTION

James Clerk Maxwell was one of the greatest physicists of all time. Yet unlike Newton with his falling apple, and Einstein with his wild hair, little seems to have permeated popular conscience of the physicist that could be said to have revolutionised the study of thermodynamics and optics, as well as electromagnetism.

This may be an oversight, or it may have been because Maxwell himself was not one to paint himself in such a public light. Regardless, it is of little doubt that Maxwell has had an indelible influence on physics. In a single stroke of genius, Maxwell unified three apparently very different physical phenomena: electricity, magnetism, and optics, which had a profound impact on all of the physics that followed. But while his name is ubiquitous in the theory of electricity and magnetism, as well as the kinetic theory of gases, Maxwell also proved invaluable in his contributions to other areas. Not only did his work in electromagnetic waves change the field of optics, he also did much research in colour theory itself. He also delved into geometry and other areas. Nor did his contributions end there.

In this essay, we briefly examine several of his more notable contributions outside of those in electromagnetism that he is so well-known for.

LIFE AT GLENAIR

Born at a time when science was mostly a pursuit of the rich, Maxwell was fortunate in that his family had financial security on which to depend. His technologically minded father, John Clerk Maxwell, had built Glenlair when he’d chosen to return to the historical family seat in the Scottish countryside. Glenlair would prove to be Maxwell’s true home, no matter which Colleges and Universities he later attended or taught at. It was also the place where his early curiosity was allowed to shine [1].

Perhaps because his mother passed away at an early age, Maxwell was especially close to his father. During his school years when he could, he would return to Glenlair for the holidays. After his father had passed, Maxwell frequently returned to Glenlair during breaks. There was much important work done at Glenlair in those times. One of the reasons that Maxwell resigned from his position at King’s College, London was to return to Glenlair and rebuild it, as his father had always wanted. (In the end, due to lack of money, his father’s dreams would not be realised.) The other reason was that teaching did not give the flexibility he needed to pursue his scientific pursuits—all of which he did at Glenlair. During this time, his primary connection with the scientific community was by copious mail [2].

However, while Glenlair was Maxwell’s seat in the country, much of his life and work occurred elsewhere as well.

SCHOOL DAYS

Because of his father’s reluctance to part with young Maxwell, he did not enroll in school right away. This gave Maxwell a rocky start to his formal education. Yet, while it may not have been enjoyable, it was not all negative. Outside of school, Maxwell often had his father with him on the Saturday half holidays.

His father, ever an encouraging presence, took him to see the newest technology of the time, to explore, and most
importantly, to attend meetings—including scientific meetings—of the Royal Society of Edinburgh. The particular importance of the latter would be the introduction of young Maxwell to the cream of Edinburgh’s scientific crop. At the age of fourteen, Maxwell, in answer to a problem, wrote a paper entitled ‘On the Description of Oval Curves, and those Having a Plurality of Foci’. This would prove indispensable to Maxwell’s scientific development [1].

In particular, he was introduced to James Forbes [3]. Instead of proceeding to university in Oxbridge, Maxwell opted to study at a Scottish university for law, partly because Oxbridge was far from home and his father, and partly because law was an actual job, while science was not. However, this in turn meant that during his time at Edinburgh University, he was able to develop the basis of his scientific process. James Forbes was the Professor of Natural Philosophy. Having been alerted to Maxwell’s genius, Forbes gave Maxwell the run of his own laboratory. During the time Maxwell was a student, and indeed, for some time after, instructions in experimental techniques was not the norm, and very few students had access to equipment. This allowed Maxwell to develop experimental skills and instilled in him the basis of his experimental training. Another influence was the physician Sir William Hamilton, who along with the philosophical training common to Scottish universities, helped develop Maxwell’s way of thinking [1].

More specifically, it was during this time at Edinburgh that Maxwell delved deeply into his research in colour theory. Forbes himself was doing experiments on colour vision, which Maxwell assisted with. Maxwell developed several of his own theories in colour theory later as well. He would also eventually revolutionise the field of optics with his work on electromagnetic waves.

**SATURN’S RINGS & THE MOLECULAR THEORY OF GASSES, a.k.a. THE BIRTH OF MAXWELL’S DEMON**

If one were to trace Maxwell’s work on the molecular theory of gasses to the very beginning, Campbell and Garnett say that it would be the discovery of the planet Neptune [1]. More directly however, was the prize that was set up as a result of the bickering that occurred over the discovery—the Adams prize. In 1855, the Adams prize topic was set to be “The Motions of Saturn’s Rings”—how and why do Saturn’s Rings exist in the way they do? This was a problem that would consume much of Maxwell’s time in between his formal responsibilities for four years. While the calculations were tedious, a brief explanation of his work and how it would influence one of his greatest contributions, need not be. While a model consisting of rigid rings makes for simple mathematics, physically, it seemed unlikely. On the other hand, a fluid ring would break up into a chain of fluid drops. This led Maxwell to consider a ring of many particles [2].

Perhaps here would be a good place to mention a number of Maxwell’s friends. During Maxwell’s time at school and after, he developed a friendship with, and would continue correspondence with several men who would all be formative influences. Tait, Thomson, Campbell, and Stokes were among these. In particular, Maxwell often corresponded with fellow Scottish physicists Tait and Thomson. One point of note is that the three often corresponded using ½d postcards, saving ½d on each letter—this lead to a quirky shorthand developed to save space. Not only their names—Tait became ‘T’, Thomson was referred to as ‘T’, and Maxwell as dp/dt—even the contents were often reduced to symbols. In a time without email and telephones, this type of correspondence can be seen as a precursor to today’s collaboration in physics [1]. It was in the matter of his molecular theory and work on Saturn’s rings that he corresponded as well with his friends. Perhaps this was less than ethical, as Thomson was one of the judges for the prize [1]. However, in the end, Maxwell did produce the suitable mathematical model for the rings (his predictions were later confirmed by Voyager flybys in the 1980s), and in the process, developed the basis for the kinetic theory of gasses that he would continue to develop further in his later years. Of course, these results are well known. It is in this area that the famous Maxwell’s Demon came to be.

Here is a thought experiment. Consider a container of gas molecules that is separated into two halves by a thin wall, with hot molecules on one side and cold molecules on another (see diagram on next page). By the 2nd law of thermodynamics, it can only be possible for the hot side to become cooler while the cold side becomes warmer, until both sides reach the same temperature (establish thermal equilibrium). Maxwell proposed the existence of a “demon” that could, after the two halves had reached thermal equilibrium, open a door between the two halves to allow hot molecules to pass from the left side to the right, but otherwise keep the door closed. This way, the demon could have “the hot system [grow] hotter and the cold colder, yet no work [will have] been done, only the intelligence of a very observant and neat-fingered being has been employed.” In other words, if one were fast enough, the 2nd law of thermodynamics could be violated, “only we can’t, not being clever enough.” [1]

Maxwell’s Demon would plague physicists for quite some time. And all this having started from the discovery of a faraway planet!
MAXWELL, PROFESSOR OF EXPERIMENTAL PHYSICS

Maxwell himself had the benefit of a laboratory while in university, a perk that while common to undergraduate students now, was a rarity to English students at the time. However, it was quickly becoming clear that it was important to have students educated in the ways of laboratory techniques, and to experience firsthand experiments that they had previously only ever learned about through books and equations. It was, however, a slow change—yet in 1868, when Oxford University began to push laboratories for their physics students, it was only natural that Cambridge would follow [1].

Maxwell was not Cambridge's first choice to be the Cavendish Professor of Experimental Physics. It was a post first offered to Thomson and Helmholtz, who both turned it down. When Maxwell was appointed, there was as of yet no laboratory. In fact, the very idea of a laboratory where undergraduate students could perform experiments might have been scrapped had the Chancellor of the University, the Duke of Devonshire William Cavendish (descendent of Henry Cavendish), not offered to pay for the expenses himself [1].

Maxwell’s contribution was in the design and furnishing of the laboratory. Having benefited from a laboratory in his own studies, and having now seen many other practical laboratories, Maxwell could specify to the architect the sort of building that was needed. In the end, he also paid for several apparatuses out of his own pocket. But beyond the furnishing, Maxwell was also a strong proponent of experiment as a method of instruction. Although such a method of instruction was by then somewhat established, it was by no means viewed as necessary. What Maxwell did at Cambridge was to work to establish the necessity of science, including experimental science, at a student level.

Through his work with Cambridge’s physics laboratory, Maxwell made an important contribution to the training of students using experiments. However, this is somewhat ironic, as it could be said that basically Maxwell was far more of a theoretician than an experimentalist. He was not necessarily a practical man, but his training in philosophy and science prodded him to question. Whatever Maxwell’s own tendencies, the Cambridge laboratory would serve physics undergraduates for the better part of a century, in itself a remarkable feat.

MAXWELL, THE PERSON

At thirty five, Maxwell was described as “a man of middle height, with frame strongly knit, and a certain spring and elasticity in his gait. . . He had a strong sense of humour, and a keen relish for witty or jocose repartee, but rarely betrayed enjoyment by outright laughter.” As a child, he was curious and inquisitive, an “independent minded boy” [1], who had “an uncanny way with all animals.” In later childhood, at his aunt’s house while he attended school, he “read and knitted a lot and spent hours composing letters home to his father…written in mirror-writing.” He would also come to find great pleasure in the classics, despite his rough start in Greek and Latin, and “was fond of reading aloud from his favourite authors, particularly from Shakespeare.” Maxwell himself also took pleasure in penning verse, and left behind a fair body of work.

He also, evidently, had a great distaste for the washing of anything in starch!

CONCLUSION

Although James Clerk Maxwell is a physicist of immense stature, little is known about him as a person by today's physicists—let alone the layperson. To reduce a great man to his equations alone would be a folly. His achievements and contributions are many, but too easily are they overshadowed by the twin peaks of his accomplishments in gas theory and electricity and magnetism. It pays to look beyond the equations his name has become inexorably connected with, and recognise his other achievements.

REFERENCES

Maxwell As The Catalyst For
Special Relativity

by Adam Koberinski

ABSTRACT
Maxwell thought of electromagnetism in terms of a mechanical model of electric and magnetic fields. This stemmed from the widespread belief, in Maxwell’s time, in an “ether” through which light propagated. Ironically, from Maxwell’s equations, Einstein was led to a revolutionary theory in which space and time are intimately linked, and the ether “superfluous.” We look at Maxwell’s influence on the development of Special Relativity.

MAXWELL AND THE ETHER

Prior to Newton, Christiaan Huygens had hypothesised that light is a wave propagating through an ether, an idea which Newton rejected (he favoured a model in which light is made of particles moving through vacuum). With the experiments of Young and Fresnel in the early 1800s, which showed clearly the wave nature of light, the ether idea was revived, all the more so when Maxwell discovered that light is a propagation of electromagnetic waves. Whenever one has wave propagation, the natural question is, “What is the medium through which the waves propagate?” In other words, what is “waving”? The ether! However, the ether was beneficial not just for providing a seat for electromagnetic phenomena. The Newtonian mechanical paradigm required an absolute space compared to which bodies were in motion, or not. The ether was thought to be this all-pervading backdrop against which, e.g., the planets moved. The ether was thus a succinct resolution to both of these problems, and was widely believed to exist and be detectable.

Maxwell came to prominence in a time when physics was thought to be completely mechanical and deterministic. As Laplace famously stated, for an intellect which at a certain moment would know all forces that set nature in motion, and all positions of all items of which nature is composed...nothing would be uncertain and the future, just like the past, would be present before its eyes [1]. This dictated the methodology of physics at the time, and Maxwell gained fame for his mechanical modelling of the electric and magnetic fields. He originally modelled the field lines using fluid analogies, where molecular vortices were used to model electric currents and magnetic phenomena [2]. These vortices were in part due to the ether, and in part due to the matter through which the electric or magnetic field was propagating. Using this mechanical model, Maxwell then related the constants \(\varepsilon_0\) (the electric permittivity of the vacuum) and \(\mu_0\) (the magnetic permeability of the vacuum) to the mechanical properties of the ether. These properties included the density and elasticity of the medium. By substituting the ratio, \(\varepsilon_0/\mu_0\), into Newton’s speed of sound equation, Maxwell discovered that the speed of propagation of electromagnetic waves through the ether was equal to the speed of light, which had been recently accurately measured. Thus Maxwell concluded that light is a propagating wave of electric and magnetic field oscillations. Maxwell continued on to completely unify electric and magnetic phenomena into his now famous equations of electromagnetism.

In a Newtonian universe (absolute space and time), the idea that light waves are disturbances of the ether—just like ripples in a pond of water, has consequences that can be measured, and thus tested. If there is a light source at rest relative to the ether, the light waves it emits will move at a fixed speed relative to the ether—the speed calculated by Maxwell, and built into his equations. If we, too, are at rest relative to the ether, we will see those waves pass us at that same fixed speed. However, if we are moving relative to the ether, say toward or away from the light source, we will measure a different speed: greater (if we are moving toward to source) or less (if we are moving away). Thus, it should be possible to detect our motion relative to the ether (which was assumed to be at rest in Newton’s absolute space). For example, imagine that the solar system is at rest in absolute space, and thus that the Earth moves through the ether as it orbits around the Sun. So the measured speed of light should be different depending on whether the light is travelling parallel or perpendicular to the Earth’s motion through the ether. Attempts were made to measure this effect, the most notable of these being the Michelson-Morley experiment. However, it was found that the speed of light was not affected by this putative relative motion. It seemed that the ether hypothesis had been falsified.

EINSTEIN’S RESOLUTION

After the Michelson-Morley experiment, many scientists began to doubt the existence of the ether. Somehow, light would have to be a wave mysteriously propagating through empty, absolute space, without any medium that is “waving.” Essentially independently of the results of the Michelson-Morley experiment, Einstein resolved this paradox by carefully examining the assumptions physicists were making, and using simple logic. Let’s start by imagining light is a wave-in-ether phenomenon. Then, as noted above, its speed (in a Newtonian universe, at least) will depend on the motion of the observer relative to the ether. But (and this is the key point) it will not depend on the motion of the source of light relative to the ether. This is a simple property of any wave-in-medium phenomena. For example, if we are at rest in air, sound waves from an ambulance siren will move at a fixed speed relative to the air, independent of the motion of the ambulance. We will hear a Doppler shift in the frequency of the waves, but the motion of the ambulance, say toward or away from us,
will have no effect on the speed of the waves. So Einstein assumed that, if we are at rest relative to the ether, the speed of light should be independent of the motion of the source of light waves. This was an obvious assumption to make, and easy to test experimentally. He also assumed (and this is the key assumption) that the principle of relativity applies not only to mechanical phenomena, but also to light. We experience the mechanical version of the relativity principle everyday: if we are in a room (car, airplane, etc.) that is moving with a constant velocity (no acceleration), we cannot tell that we are in motion. It feels just like we are at rest. There is no mechanical experiment we can perform inside the room that can detect its motion. Einstein simply extended this relativity principle to experiments also with light. These two assumptions (speed of light independent of the motion of the source—true for any wave-in-medium phenomenon, and a slightly extended relativity principle) would have seemed eminently reasonable to Einstein’s contemporaries. Einstein showed, however, that for these two assumptions to be logically consistent with each other requires that we do not live in a Newtonian universe. Space and time are not absolute, but are intimately intertwined in a way described in his Special Theory of Relativity.

A NEW PARADIGM

Special Relativity involves, among other things, the phenomena of “time dilation,” “length contraction,” and “relativity of simultaneity.” If you and I are at rest in separate rooms that are moving relative to each other, I will see your clock running slow relative to mine (time dilation), and will see that your room is contracted in the direction of motion relative to mine (length contraction). Moreover, these effects are reciprocal, e.g., I see your clock running slow relative to mine, and likewise you see my clock running slow relative to yours. While this is logically necessary (by the principle of relativity), it might seem counterintuitive: if I see your clock running slow, wouldn’t you see my clock running fast? The answer to this riddle lies in the third phenomenon we mentioned: relativity of simultaneity. Two events that are separated in space, and occur simultaneously for you (like snapping your fingers on your left and right hands at the same time), will not occur simultaneously for me if I am in motion relative to you. Like space and time intervals, simultaneity is relative, not absolute.

While these phenomena might seem strange, they are perfectly logical (no paradoxes of any kind arise) and ultimately perfectly sensible. Once understood, it is difficult to imagine the universe could be any other way! Einstein was the first person to achieve this understanding. Moreover, it is easy to show that time dilation, length contraction, and relativity of simultaneity work together in a simple geometrical way to enforce a speed limit in our universe—the speed of light. To appreciate what this means, imagine you are at rest in the ether and shine a light at me. The speed of the light waves I measure would seem to depend on my motion toward or away from you. But Einstein showed that the very nature of space and time themselves are such that the speed I measure does not depend on my motion relative to the ether! Contrary to common misconception, Einstein did not assume this bizarre fact—he derived it. Thus, in Einstein’s universe, it is true that the speed of light is independent of the motion of the source and the observer relative to the ether.

So where does this leave Maxwell and his electromagnetic ether? We started with the assumption that the ether exists (which implies that the speed of light is independent of the motion of the source of light) and used the principle of relativity to deduce that the speed of light is also independent of the motion of the observer, and so is a universal constant. This deduction is impossible in Newton’s absolute space and time, but is natural in Einstein’s relative space and time. In short, Special Relativity says that it is impossible to measure any motion relative to the ether (which explains the null result of the Michelson-Morley experiment). Special Relativity does not say the ether does not exist, just that its detection is impossible. Thus, Einstein said that the ether is “superfluous” (not essential)—it might exist and it might not. Within the context of Special Relativity, we cannot know. In fact, Einstein later developed the General Theory of Relativity, in which spacetime is curved. Einstein thought of the curvature of spacetime as measuring elastic properties of the ether. Contrary to common misconception, the Michelson-Morley experiment did not rule out the ether. (It would rule out the ether only in a Newtonian universe, not in an Einsteinian universe.) In fact, the ether is still a subject of active research by physicists today.

Finally, it should be pointed out that, unbeknownst to Maxwell, his equations for electromagnetism were the first equations in physics that were consistent with Einstein’s Special Relativity. Special Relativity allows for both a wave model of light (Maxwell’s wave-in-ether model) as well as a particle model of light (like Newton’s particles in a vacuum). This is important because our modern view of light is quantum mechanical, and according to the wave-particle duality of quantum mechanics, all entities (including light) have both wave-like and particle-like properties. Maxwell was decades ahead of his time, and his equations continue to serve as a model for many other physical phenomena in Einstein’s universe.

REFERENCES

“Finding” the Electromagnetic Wave—
The Life and Work of Heinrich Hertz

by Zheng Cui

ABSTRACT

The scientific unit of frequency—the “hertz,” was named in honour of the German physicist Heinrich Hertz. From early in his life, Hertz had an aptitude for science and engineering, and he studied under prominent figures such as Kirchhoff and Helmholtz. In his short life, he was a prolific researcher, particularly in the field of electromagnetism. Hertz is perhaps best known for performing experiments that gave conclusive evidence for Maxwell’s electromagnetic theory of light, despite some controversy. Hertz’s experiments confirmed the existence of electromagnetic waves that travel at a finite speed (the speed of light). He also measured the wavelength of light, and explained the reflection and refraction of electromagnetic waves. His discovery of radio waves would later revolutionize the field of wireless technology. Hertz had also studied mechanics and helped establish the photoelectric effect. Tragically, an infection ended his life when he was only 36 years old. For his contributions to electromagnetism, today his name is ubiquitous in science and engineering in honour of his discoveries.

EARLY YEARS

The short but scientifically fruitful life of Heinrich Hertz began with a wealthy and comfortable upbringing. Hertz did not face any major obstacles that would make a sensational story, and he was very gifted in many areas including mechanics, linguistics and athletics from an early age.

Hertz was well educated, as was the rest of his family, and after first pursuing engineering, he turned his interests towards physics, in which he would eventually publish his ground breaking work and become world famous.

Heinrich Rudolf Hertz was born on February 22, 1857 in Germany to a wealthy family. His parents were well educated, and his father was elected to Hamburg’s senate. Hertz was the oldest child of five. After completing secondary school, he was determined to become a structural engineer, but after serendipitously discovering literature on telegraphy, Hertz’s interests started shifting towards physics, which continued for the rest of his life.[3]

EDUCATION

Hertz’s interest in structural engineering first led him to become a civil engineering apprentice after secondary education. During this time his interests expanded and he started studying various subjects himself, ranging from economics and physiology to physics. Since Hertz had a lot of spare time at the civil engineer's office, he spent more and more time in the city's art galleries and libraries. Among the various subjects that he read extensively during this time, he became interested in telegraphy and decided to enrol in the Technical University of Dresden to study the subject.[3] Hertz soon found the level at the university was too low to suit him so he opted out to complete his one year compulsory military service. Hertz then enrolled at the Technical University of Munich as well as the University of Munich to study physics. Again he found the level of instruction too low. So he eventually transferred to the University of Berlin and studied under Hermann Helmholtz—the most prominent German physicist at the time.[3]

CAREER AND RESEARCH

After graduating summa cum laude, Hertz remained at the University of Berlin as Helmholtz’s assistant. Hertz did not accept Helmholtz’s suggestion to do a dissertation that would experimentally prove Maxwell’s formulation of electromagnetism, fearing it was too difficult. Rather, Hertz worked on induction in rotating conductors. While searching for a permanent research position, Hertz also produced two papers on elasticity, which were of prime importance in the field, but often overshadowed by his later work in electromagnetism.

Not only did Hertz distinguish himself by graduating summa cum laude—almost never awarded at the University of Berlin, Hertz also conducted an experiment to determine the mass of electrons in a current, and published the result alongside papers by the likes of Kirchhoff, Weber and
For Hertz's dissertation topic, Helmholtz proposed an experiment to determine whether a time-varying electric field would produce a magnetic field in its vicinity. But Hertz knew that no oscillator at the time would produce an electric field varying at a high enough frequency for such an experiment. Hertz published his second paper on induction in rotating spheres, and the next two on the theory of elasticity. He completed a dozen more papers while he was still in Berlin trying to build up a portfolio that would get him a more permanent position, not unlike the path that many researchers have to take today.[3]

**ELECTROMAGNETIC WAVES**

Having secured a professorship at the Technical University of Karlsruhe, Hertz resumed his research in electromagnetism. At the time, European physicists were divided in their views on the theory of electromagnetism. People who advanced Maxwell's theory were dubbed the Maxwellians, while others, who had developed electrical technology, found the theory to be too complex and mathematical. Hertz's experiment demonstrated that electromagnetic waves exist and behave according to Maxwell's theory. This ground breaking work made him instantly famous.

Maxwell published his theory of electromagnetism in 1873.[2] But even years after his death, the theory was still neither well understood nor widely accepted. Maxwell's theory was modified, demonstrated and made understandable mainly by the efforts of Heinrich Hertz and the Maxwellians (mainly George Francis FitzGerald, Oliver Lodge and Oliver Heaviside—who introduced modern vector notation).[4] Hertz and the Maxwellians were not aware of each other's work until Hertz published his seminal experiment in 1888.[4] After Hertz's individual work to modify Maxwell's theory in 1884, and to validate the theory by experiment in 1888, further efforts were made jointly by Hertz and the Maxwellians to develop Maxwell's theory and transform it into the powerful and concise form that we know today as the four Maxwell equations in vector calculus form.[4][2]

After Berlin, Hertz joined the University of Kiel as a researcher under the promise that the position would soon be upgraded to a professorship. The facility for research was unsatisfactory at best, and Hertz soon became depressed. Nevertheless, while at Kiel, Hertz still produced one important paper in 1884 to modify Maxwell's theory of electromagnetism. After two years, Hertz finally received an offer for a full professorship at the Technical University of Karlsruhe, which he promptly accepted.

Hertz flourished at Karlsruhe, both personally and academically. He met and married his wife and resumed his experimental work from Berlin. In a series of experiments, Hertz effectively created the first radio system, measured the velocity and wavelength of electromagnetic waves and how they reflect and refract, and also demonstrated the similarities between light and the electromagnetic waves.[5] He then received offers from many places including Berlin, but chose Bonn to continue his experimental research.[1] During an invitation to London, he finally met the Maxwellians in person, with whom he had corresponded.[3]

**LATER RESEARCH AND ILLNESS**

After Hertz's discovery, many proposals were made for the practical applications of electromagnetic waves in communication technology. Unfortunately at the time Hertz could not conceive of a way that such an application could be made. Hertz also attempted to reformulate the entire foundation of mechanics, exploring the implications of Maxwell’s electrodynamics. His theory found little favor among physicists although it was logically self-consistent. Although Hertz's life was short, his intellectual legacy remains today.

In 1889 a German engineer, Heinrich Huber, wrote to Hertz suggesting the use of radio waves to transmit power and to telephone. Hertz replied that this was not practical due to the extraordinarily long wavelengths. However, his logical but faulty reply did not hinder the development of radiotelegraphy. Despite Hertz's experimental brilliance, he stayed away from practical applications.[3]

In the early years of 1890s, Hertz was troubled by a jaw infection. The illness took such a bad turn that he gave up lecturing altogether. On New Year's day of 1984 Hertz finally succumbed to the illness, due to blood poisoning. [3] For Hertz's contribution in the development of the modern theory on electromagnetism, his name is used ubiquitously as the unit of frequency. Even though Hertz lived a short life, he was scientifically fruitful and his work influenced the development of physics profoundly.

**REFERENCES**


Person of Interest: Colleen Gilhuly

Introduction by the Editor

Our person of interest in this issue is Colleen Gilhuly, a fourth-year physics student at the University of Waterloo, who recently attended the inaugural Canadian Conference for Undergraduate Women in Physics (CCUWiP) in Montreal. Her report on her experiences, and her advice, may be of interest to many physics students, especially female students. Colleen writes:

I recently had the opportunity to attend the first ever Canadian Conference for Undergraduate Women in Physics (CCUWiP) in Montreal, January 10-12. Organized and held at McGill University, the aim of the conference was to facilitate career exploration, peer networking, and to showcase undergraduate research in physics. Fifty-two female students from Ontario and Quebec universities attended.

While somewhat smaller than the long-running CUPC (Canadian Undergraduate Physics Conference), the CCUWiP distinguishes itself not only in the gender of attendees, but in the focus on careers and community, in addition to research.

The variety of speakers was amazing. All speakers had their beginnings in physics, but their career paths took them in many different directions. Potential career paths in patent law, particle accelerators, consulting, materials science, and human resources were showcased, in addition to the traditional academic path. It was very interesting to hear how problem solving skills learned in physics programs can be so widely applied. If nothing else, I now have a convenient list of potential careers to give to my father when he asks how I am going to make any money as a physicist!

The panel on career paths and “life challenges” was surprisingly honest and personal. It was reassuring to hear that the speakers found that they were at no disadvantage (or special advantage) as women studying physics. One of the big messages of the panel was that it is very common to feel overwhelmed, and that does not make you a bad physicist. I really appreciated that the conference did not have a “girl power” theme. It instead focused on encouraging young women to pursue their interests without doubting themselves.

During meal and coffee breaks, networking with the speakers and my 51 fellow students occurred very naturally. Conversing in small groups over meals was one of my favourite parts of the conference. I am in the co-operative education program at the University of Waterloo, which combines academic studies with real world job experience, and I found myself giving a lot of co-op related advice to younger students.

An informal panel of upper-year undergraduates might have fit in very well with the spirit of this conference, and it is one of the only things I would say was missing.

At the CCUWiP, I presented my work on radiograph image analysis, carried out during a co-op work term at Health Canada. A series of exposures of contaminated filters had been produced, with dark spots corresponding to the location of radioactive particles. My work was heavily based in simulations and programming, attempting to find a measurement method to characterize spots and estimate the size of the particles causing the spots. I had the opportunity to chat with several interested students before I had to rush away to the bus terminal. I really enjoyed sharing my work with others. I was also very impressed with the level of research presented by my peers. This would be a great opportunity for first- and second-year students to explore possible co-op or summer research projects. The environment was very supportive and low pressure, and would be a good introduction to scientific conferences for students hesitant to present in a competition or in front of a large group.

All expenses in Montreal were covered by the sponsors of the conference for a small registration fee. Thanks to the support of the Physics and Astronomy Department at Waterloo, my travel costs were also covered. Therefore, this is a very accessible conference to students.

I must end by saying again that this is only the first year that the CCUWiP has been held. The organizing committee did an excellent job establishing this conference. I hope that it becomes an annual event, travelling to different universities across Canada so that female physics students from all parts of the country can make the journey at least once. I would recommend it for students in any year of their studies.

—Colleen Gilhuly

The SIN Bin

by Chris O’Donovan

Here is the solution to last issue’s SIN Bin involving a ball bouncing off a wall along with a new SIN Bin question involving three masses connected in various ways.

SIN Bin #147

Consider the system of masses depicted to the right. The string connecting \( m_2 \) and \( m_3 \) is light and inextensible and the pulley is small, light and frictionless. All contact surfaces are also frictionless. (a) What force, \( \vec{F} \), is required for the mass \( m_3 \) to have no vertical motion? (b) In the absence of the force, what is the acceleration of \( m_1 \)?

SIN Bin #146 Solution

Consider a small ball with an initial velocity, \( \vec{v}_0 \), which makes an angle \( \theta \) to the horizontal plane. It’s trajectory would be a parabola if it weren’t for the vertical wall which is perpendicular to the plane of the ball’s trajectory. The ball bounces
off the wall in an elastic collision so that the horizontal component of its velocity at the moment of impact reverses and its vertical component remains unchanged. If the wall is a distance \( x_w \) from the initial position of the ball, how far, \( x_f \), from the ball’s starting point will it impact the plane? (Hint: Check that you get the correct answer for the special case \( x_w = \frac{v_o^2}{2g} \sin 2\theta \), for which the impact occurs at the top of the trajectory.)

The initial trajectory is given by
\[
\begin{align*}
 x(t) &= v_o t \sin \theta \\
y(t) &= v_o t \cos \theta - \frac{1}{2} gt^2
\end{align*}
\]
where we have taken the origin at the ball’s initial position.

This is the parametric equation for a parabola (with the time, \( t \), as the parameter)—if we eliminated \( t \) from these equations the result for \( y \) would be quadratic in \( x \).

The velocity is the derivative of the position,
\[
\begin{align*}
 \dot{x}(t) &= v_o \sin \theta \\
 \dot{y}(t) &= v_o \cos \theta - gt.
\end{align*}
\]
If there was no wall then the ball would strike the ground at \( t = t_i \) and
\[
y(t_i) = 0 = v_o t_i \cos \theta - \frac{1}{2} gt_i^2 \Rightarrow t_i = \frac{2v_o \cos \theta}{g}
\]
and the horizontal position would be
\[
x_i = x(t_i) = v_o \left( \frac{2v_o \cos \theta}{g} \right) \sin \theta = \frac{v_o^2}{g} \sin 2\theta
\]
which, of course, is the known solution for this standard problem.

When the wall is present the ball will strike the wall when
\[
x_w \equiv x(t_w) = v_o t_w \sin \theta \Rightarrow t_w = \frac{x_w}{v_o \sin \theta}
\]
and at height
\[
y_w \equiv y(t_w) = x_w \cot \theta - \frac{g x_w^2}{2v_o^2 \sin^2 \theta},
\]
so the moment before the impact we have for the velocity
\[
\begin{align*}
 \dot{x}(t_w) &= v_o \sin \theta \\
 \dot{y}(t_w) &= v_o \cos \theta - \frac{g x_w}{v_o \sin \theta}.
\end{align*}
\]
The moment after the impact the horizontal component of the velocity is reversed and we now have a new trajectory with initial position \((x_w, y_w)\) and initial velocity
\[
\begin{align*}
 v_x &\equiv -v_o \sin \theta \\
v_y &\equiv v_o \cos \theta - \frac{g x_w}{v_o \sin \theta}.
\end{align*}
\]
It is convenient to use a new time variable, \( \tau \), for this second part of the trajectory with this initial position and velocity. We have for the position,
\[
\begin{align*}
 x(\tau) &= x_w + v_x \tau \\
y(\tau) &= y_w + v_y \tau - \frac{1}{2} g \tau^2
\end{align*}
\]
and the ball will strike the ground when \( \tau = t_f \) and \( y(\tau) = 0 \). For \( y(\tau) = 0 \) we have a quadratic equation in \( \tau \) with solutions
\[
\tau = \frac{v_y}{g} \left( 1 \pm \sqrt{1 + \frac{2gy_w}{v_y^2}} \right).
\]
We want the positive solution (the negative solution corresponds to projecting this trajectory on the other side of the wall), so the final horizontal position is
\[
x_f = x_w + \frac{v_x v_y}{g} \left( 1 \pm \sqrt{1 + \frac{2gy_w}{v_y^2}} \right)
\]
into which we need to substitute our expressions for the height and velocity at the moment after impact (i.e. \( y_w, v_x \) & \( v_y \)).

This looks like quite the mess—however, upon substitution of our expressions for the height and vertical speed the radical can be simplified,
\[
1 + \frac{2gy_w}{v_y^2} = \left( \frac{v_o \cos \theta}{v_y} \right)^2.
\]
The final horizontal position is then
\[
x_f = 2x_w - \frac{v_o^2}{g} \sin 2\theta
\]
which is surprisingly simple considering the prior expression for \( x_f \). For the special case \( x_w = \frac{v_o^2}{2g} \sin 2\theta \) it is easy to see that \( x_f = 0 \), as expected.

Figure 1: The ball’s trajectory (solid green curve) when it bounces off the wall (vertical blue line) can be mirrored in the wall (dashed green curves). It is then a simple matter to relate the distance between the starting and ending positions of the ball, \( x_f \), to the distance to the wall, \( x_w \), and that of the final position in the absence of the wall, \( x_f \).

The absence of any radicals in the ultimate solution leads us to wonder if there is a simpler method to solve this problem. For the problem without the wall we found
\[
x^*_f = \frac{v_o^2}{g} \sin 2\theta.
\]
The similarity to the solution to the given problem leads us to plot the two trajectories, with and without the wall. When we do so (see Fig. 1) we see that the wall behaves somewhat like a mirror and that the distance of the final impacts from the wall for the two trajectories are the same so
\[
x_w + (x_w - x_f) = x_f^* \Rightarrow x_i = 2x_w - x_f^*
\]
which, since \( x_f^* = \frac{v_o^2}{2g} \sin 2\theta \), agrees with the boxed equation above and is a much simpler method.
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Solution to the Puzzle Corner:

The linked Laureates from A to Z are as shown, with the years of their awards indicated below the names.

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Biographies and award citations of these Physics Laureates may be found on the official website of the Nobel Foundation:
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