James Clerk Maxwell

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James was born on June 13, 1831, in Edinburgh *(ED-in-bur-uh)*, Scotland. His parents, John and Frances, came from families that had inherited quite a bit of farm land. They were not rich, but they were far from poor. The family name had originally been just "Clerk" (which in Scotland is pronounced like "Clark"). John had been obliged to add "Maxwell" to his surname in order inherit some property. Someone many generations back had put a legal requirement on that land, stating that whoever owned that land must be named Maxwell. If your name wasn't Maxwell, you'd have to change it. So even though John was the rightful heir, he still had to change his name to "Clerk Maxwell."

You can look back at this map later, when other places are mentioned.

John Clerk Maxwell's property included a manor house called Glenlair. When James was about 3 years old, John decided to move the family from their house in the city at 14 India Street (which is now a museum) out to Glenlair. There were many acres of farm land around the house, as well as areas of woods and streams. It was at Glenlair that James spent most of his childhood.

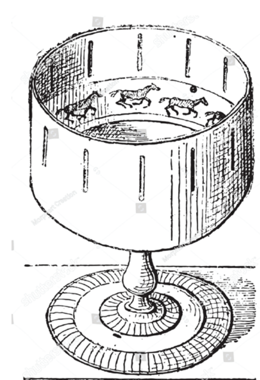

James with his mother, Frances

All children are curious, but James was exceptionally curious. He wanted to know exactly how everything worked. His mother wrote that he was always asking, "What is the go of that?" (Meaning, "What makes it go?") If the answer did not satisfy his curiosity, he would then ask, "But what is the particular go of it?" He would pester not only his parents, but every hired hand on the property, wanting to know all the details about every aspect of farm life. He helped with farm chores outside, and with indoor activities like basket making, knitting, and baking.

One day, little James was given a metal pie pan to play with. As he turned it over in his hands, he noticed that sunlight was being reflected off the pan and onto the ceiling. This delighted him to no end and he ran to tell his mother that he had found a way to bring the sun inside.

James grew up as an only child, but he had several cousins that he was close to. His cousin Jemima was a few years older, but close enough in age that they spent many happy hours playing together. They were both artistic, and Jemima grew up to be a professional artist. They also enjoyed one of the latest toys, a zoetrope. They would draw their own picture strips to put into their zoetrope. The zoetrope was one of the earliest forms of animation.

Jemima painted her memories of how they played in the creek. She also made this sketch of the family dog, Toby.


This is a zoetrope.

James learned to read very quickly. His parents chose to keep him at home instead of sending him to school, so that he would have plenty of time to read on his own. They had a good collection of books in the house and James read a lot of history, geography and literature, including the Bible, Shakespeare and John Milton. He was also good at memorizing, and by the age of 8 he had memorized the entire 119th Psalm (which is 176 verses long) and other passages of Scripture, as well. Religion was important to the family, and they not only went to church every Sunday, but gathered the whole household for prayer every day.

James loved dogs. The family dog was always named Toby.

In an age without radio or television, family entertainment would often include reading novels or poetry out loud, or acting out scenes from a play. James developed an appreciation for poetry and would often write poems in later life. The Maxwells entertained guests frequently, so James learned how to behave properly at fancy dinners. There were also many communities events to go to, such as fairs and dances.

James' childhood was idyllic until the tragic death of his mother from stomach cancer when he was 8 years old. (Sadly, years later, James would die at the same age his mother did, and of the very same disease.) Even after her death, life at Glenlair continued to be good, but James missed his mother deeply. James' parents had intended to teach him at home until he was 13, then send him to the university. In those days, teenagers sometimes went off to college as young as 14 or 15 if there was not a suitable school nearby. John dreaded the loneliness he would experience if James was sent away to school, but as a busy lawyer he did not have the time to teach James himself. So John decided to hire a tutor.

The only suitable person in the neighborhood was a 16-year-old boy who had just finished his education and done very well on all his final exams. It was not uncommon back then to hire teenagers as tutors for younger children, so this decision seemed to make sense. This young tutor turned out to be a disaster, however. The tutor was harsh with James and made him memorize and recite many things that James thought were pointless. If James made a mistake, the tutor would give him a hard smack. Doubtless, the tutor had himself been treated this way in school and thought that this was the correct way to teach. James hated this method of schooling and after putting up with it for over a year, he could finally take it no longer. One day, right in the middle of a lesson, 10-year old James ran out of the house and got into one of the tubs that he and Jemima used as boats, and paddled out into the middle of the duck pond. (The pond was much larger than shown in this drawing.) The tutor shouted and threatened from the shore, but James would not come back. This incident made James' father realize how much James disliked the situation. The tutor was sent away and James went back to learning on his own.

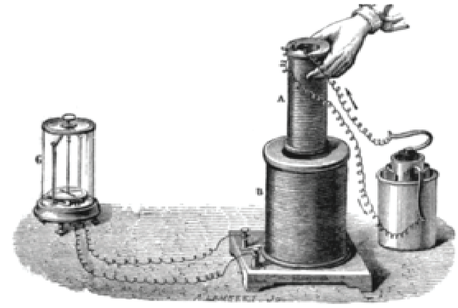
A drawing by James' cousin, Jemima Wedderburn.

When James was about 13, his Aunt Jane (his mother's younger sister) thought it was high time that James was sent to school, so she proposed a plan. Another aunt, Isabella, lived just down the street from the Edinburgh Academy (photo shown here). James could stay with her during the school terms then return home during the summer and during holidays. John agreed that James needed was now old enough to need excellent teachers, so he agreed to the plan.

When James arrived for his first day of school, he was dressed in his farm clothes, which were warm and comfortable, but not very fashionable. The older boys immediately saw James as a target for teasing. After a rough start at school, James' aunts stepped in and bought him a wardrobe of proper city clothes so he would not look different. They could not do anything about his country accent, however, which had earned him the nickname "Daftie" from his classmates. During recess, James would often wander off by himself to observe insects or climb trees.

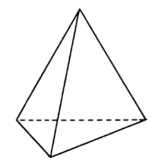
Even in this improved school environment, James still found classroom learning dull compared to reading books from his aunt's library. School education consisted mainly of memorizing Greek and Latin words, and doing arithmetic, neither of which James liked. However, James managed to win a prize at the end of the year, getting the top award in the category of Scripture biography (people of the Bible). He got this prize again in his second year, also. As the third year began, he was introduced to geometry, a subject he immediately liked and was very good at.

One Saturday, James' father came to visit him in Edinburgh. He took James to an exhibition of new inventions called "electromagnetic devices." The early 1830s had seen Michael Faraday discover that there was a connection between electric current and magnetism. He had produced magnetism from an electricity, and electricity from magnetism. In 1833, when James was just 2 years old, a practical use was found for temporary "electromagnets" that could be turned on and off: they were used to make a communication device called a telegraph. Samuel Morse wrote a dot and dash code that could be used to transmit words over an electric wire. Soon telegraph wires stretched from city to city. James was very interested in how these machines worked. Later in his life he would help Faraday complete the theory of electromagnetism.



A device that uses a magnet passing through a coil of wire to produce an electric current.

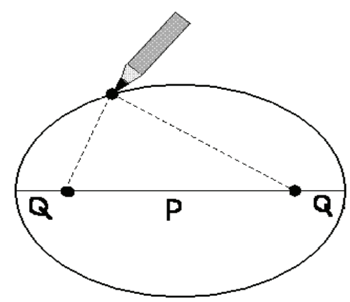
When James was 13, he discovered geometric polyhedra. He made a tetrahedron (4-sided figure) and a dodecahedron (12-sided figure) out of cardboard and mentioned them in a letter that he wrote to his father. He learned that there are only five regular polyhedra (with number of sides 6, 8, 10, 12 and 20) but these can be used to make other more complex shapes. From this time on, mathematics began to interest him more and more, and the following year he began studying ellipses by making them with pins and string.



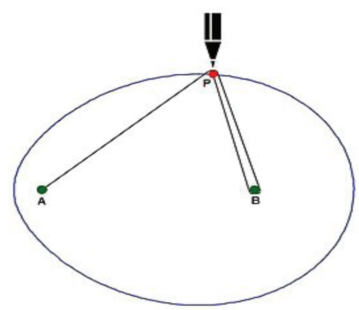
tetrahedron

Also at this time, James made his first lifetime friend. One of his classmates, Lewis Campbell, moved with his family to a house almost next door to where James lived with Aunt Isabella. James could not only walk to and from school with Lewis, but spend after school time with him as well. Lewis was one of the top students in the class, and James was thrilled to have someone his own age who shared his interests and abilities. Lewis introduced him to another friend, Peter Tait, who would not only become another lifetime friend, but would also become one of Britain's top physicists of that century. James and Peter would challenge each other with mathematical puzzles. One puzzle they never found an answer to was how to make a mirror that would not reverse your face.

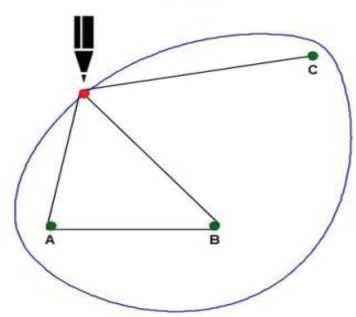
When James was 14, he became almost obsessed with drawing ellipses. An ellipse is sort of a flattened circle. James found that he could draw an almost perfect ellipse by using two pins, a piece of string, and a pencil. He tied a piece of string loosely between the pins, then pressed the pencil against the string and moved it along, keeping the string tight. If he made the pins close together, he got a very round ellipse. If he put the pins far apart, he got a long, thin ellipse. Then he realized that there was a way to describe what he was drawing just by using numbers. Math could be used almost like a language. For example, "P + 2Q= S" says that the length of the string, S, is equal to the distance between the two pins, P, plus twice the distance Q, between a pin and the edge.



Then he started thinking about ways he could continue to experiment. He untied one end of string from the pin and put it on the pencil. He looped the string round the other pin, then pushed it tight against the top part of the string. This arrangement made an ellipse-like shape called a Cartesian oval. A mathematician named Rene Descartes had discovered this shape back in the 1600s. James was probably unaware of Descartes' work at this point. Quite on his own, James decided to figure out a way to explain an ellipse with a math equation . After succeeding in that, James then experimented with adding a third pin. He went on to experiment with four pins, then five. He took notes on each experiment and began to find ways to summarize all of his findings with math formulas.



When James showed his father what he had been working on, his father was very impressed. He took James' papers to a friend who was a professor at Edinburgh University. The professor was also very impressed and realized that James' work could be turned into a published paper. Several math professors then helped James to polish his theories and get them ready to submit to a printer. One of the professors read the paper to the Royal Society of Edinburgh. This was the first of many publications that James would produce in his lifetime.



After the publication of the ellipse paper, James became interested in the writings of Descartes. After Descartes, he went on to read other mathematicians and scientists of previous centuries. He felt a kinship with them, almost as if they were his friends. He didn't idolize them, however, and was very aware that even these great men had made mistakes. (He had found a small error in one of Descartes' calculations.) James knew that he, himself, sometimes made mistakes in his equations and calculations, and resovlved never to become prideful about his work. (He would keep this promise to himself and people would later remark how amazingly humble this great man was.)

He was in many ways still a playful boy in his first year or two at the academy. His letters to this father during this time often included silly jokes. He thought it was fun to mix up the letters in his name and make an anagram. For instance, once he signed his letter as "Jas Alex McMerkwell." Once he even included the mailman in his jokes and wrote the address of Glenlair as "Postyknowswhere."

His last years at the Edinburgh Academy were very successful. Not only did he do well in math, he also won prizes in the categories of history, geography and French. He wrote poems for fun and continued to read great literature. When school was not in session, James was at home in Glenlair, helping his father to maintain the house, the barns and the land. No job was too small for him to attend to, and no employee of the famr was unimportant. James was a helper and friend to all.

James' cousin, Jemima had grown to adulthood during this time, and was now married to a mathematician named Hugh Blackburn, a professor at Glasgow University. (Notice the drawing shown here on the right, by Jemima, showing Hugh taking her picture with a camera. Photography had been invented already, and James would some day make a contribution to the development of color photography.) On one of these visits to see Jemima and Hugh, James met the youngest professor at Glasgow, William Thomson, who was only 22 at the time. James and William struck up a friendship that would last for the rest of their lives. Thomson would eventually become "Lord Kelvin," the person for whom the Kelvin temperature scale was named. (Kelvin degrees are similar to Celsius degrees.)

Photo of Hugh Blackburn

Drawing by Jemima showing Hugh taking her picture.

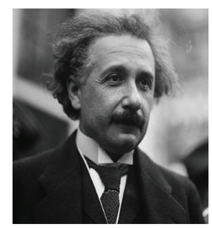
After graduation from the academy at age 16, James was ready to begin studying at Edinburgh University. His father wanted him to keep up the family tradition and study law. This might sound to use like his father was being selfish or unreasonable, but he really wasn't. Back then, you couldn't study science in the way that you can today. The word "science" wasn't even in use yet; scientists were called "natural philosophers." Natural philosophy was seen as more of a hobby than an employment, and the people who dabbled in the natural sciences were either clergy (in the church) who didn't mind being poor, or they were people who were born wealthy and had lots of time and money to spend on their hobbies. The Maxwell family wasn't poor, but they did need to have jobs that brought in a decent income. James would have to find a career that paid well. And James had proved himself to be very well-rounded in his abilties, excelling at all subjects, not just math. He would be able to do anything he set his mind to. Thus, James went off to the university, thinking that we would be a lawyer some day, just like his father.

Edinburgh University *(remember, it's pronounced "ED-in-bur-uh")*

2

At Edinburgh University, it was back to studying history, geography, Greek, Latin, and philosophy. These subjects were considered to be foundational for any career, whether it be in law, medicine, theology or teaching. His classes explored many philosophical questions and James enjoyed the lively discussion and debates among the students. Philosophers at this time were starting to ask questions like, "How can we know that we know something?" and "Can the tools of logic be applied to philosophy and theology (the study of God)?" A German philosopher named Immanuel Kant had just proposed that all knowledge is relative, and the only thing we can know about something is its relationship to other things. James thought about this deeply and, without coming to any conclusions about whether it was true or not in a philosophical sense, explored how this might be applied to material things-- to matter itself. James wrote in an essay for his class, "The only thing that can be directly perceived by the senses is Force, to which may be reduced light, heat, electricity, sound and all the other things which can be perceived by the senses." James was pondering the fact that we can't actually "sense" matter itself. We see the light that bounces off it, we hear sound waves that it produces, we see the needle on the scale go up when we weigh it, we feel sensations in the nerves of our skin when we hold it. But what is matter? Matter itself can't be perceived by the senses, only the forces that matter produces can be sensed.

James would remember this essay in later years when he was asked to review a book by his friends William Thomson and Peter Tait. He suggested that they had made an error in their book in saying that matter itself can be perceived by the senses. The structure of the atom was unknown at this point, so this was all speculation.



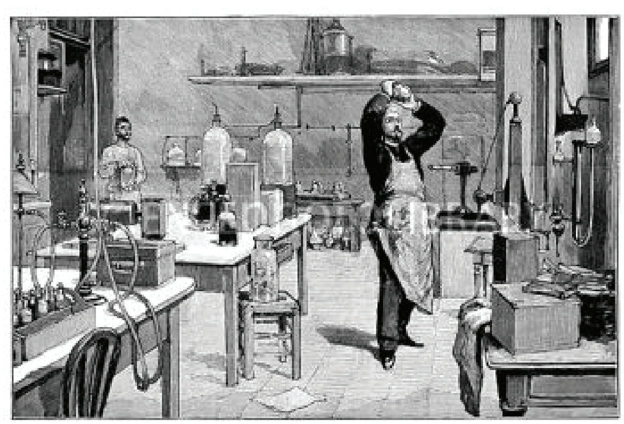
Albert Einstein

James' thoughts about matter could easily have led him into discovering the theory of relativity, had he lived a few more decades than he did. Einsteins' theory of relativity in 1905 (the year in which Maxwell should have turned 74) eventually led to the conclusion that matter could become energy and energy could become matter, a revolutionary idea. Had Maxwell lived longer, he might well have come to this conclusion himself, and could have taken Einstein's place in history as the discoverer of relativity. Einstein understood this, and he kept a picture of his hero, James Clerk Maxwell, on the wall in his office, as if to include Maxwell as a rightful co-founder of the theory.

Professor James Forbes

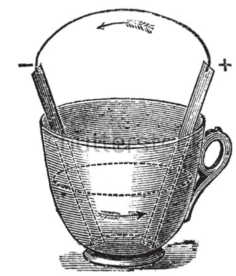
There was another side to Maxwell's academic life at Edinburgh University. Classes were mostly about thinking and writing, but one professor, James Forbes, taught his students by using experiments and what we could call "hands-on" demonstrations. He encouraged his students to get their hands dirty and try things to see if they worked. He allowed James to have complete access to the laboratory and try any experiment he wanted to do. James learned to use all the tools and machines in the lab. This method of teaching would someday become James' own method of teaching. As a professor, James would say, "Never discourage someone from trying an experiment; if they don't find what they are looking for, they may find something else just as important."

James Forbes was very much like James Maxwell, and had a great sense of adventure. He would take students on hiking trips to explore natural landmarks. Forbes was interested in geology and was a pioneer in the fields of seismology (sound waves in the crust of the earth) and the study of glaciers. Forbes was also a good writer and would help James to edit his papers to make them more understandable to the readers. Forbes was a great source of inspiration to James and shaped his life significantly.



James would do a lot of teaching in future years. He believed in exposing children to science at a young age. He would recommend that if any child has an interest in science, a visit to a "real man of science in his laboratory" can be a turning point. Don't worry that the child can't understand all the explanations, he would say. It is more important to see how a "man of science" does not get angry when something goes wrong, but patiently tries to figure out why he got those results.

Back in the early 1800s, university students often came from rural families who needed help during the summer months. Edinburgh University took great pride in the fact that they had many students from farming families enrolled as students. They believed in education for all, no matter how rich or poor a family was. The university would close from the end of April until the end of October so that students could go home and help on their family farms. So James found himself back at Glenlair only half a year after he started. He was expected to keep up his learning at home during the summer, and was given a supply of books from the school library. He also brought home some lab supplies so that he could continue his experimenting. He set up a temporary workshop above the wash house, and used an old door and some barrels as his workbench. There was a panel in the roof that would slide open to let light in and fumes out. In a letter to Lewis Campbell he described his supplies: "bowls, jugs, plates, jam jars, water, salt, soda, sulphuric acid, broken glass, copper and zinc plates, bees' wax, clay, rosin, charcoal, a lens, a Galvanic apparatus *(the battery of that day)*, and a countless variety of little beetle, spiders, and woodlice that fall into different liquids and poison themselves." James' family called his lab "Jamesie's dirt."



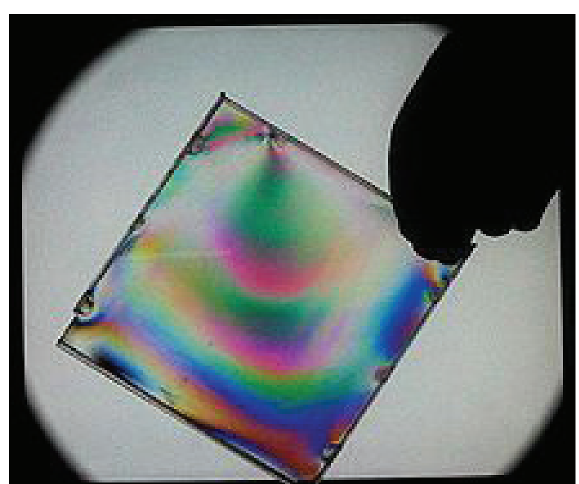
James would have made simple voltaic cells from ordinary kitchen items.

The battery of that day was a jar of acidic liquid into which was placed bars of metal, usually copper and zinc. The atoms of zinc would begin to dissolve and release free electrons that would then migrate over to the copper plates. The moving electrons were the source of the electric current. James had learned how to electro-plate objects using battery power, so he made more battery jars by copper plating old jam jars. He also dabbled in other chemistry experiments and would entertain the local children by mixing white powders that would turn green when you spit on them.

As much as he liked chemistry and electricity, the experiments that interested James the most at this point in his life were the ones that used polarized light. Of course, no one knew yet what light really was. (It would be James himself who would figure that out in later years.) But much was known about how light behaves. Isaac Newton had shown that light is made of a complete spectrum of colors. Light can be bent by a prism, with each color bending a different amount, allowing the colors to be displayed in a band that we call a rainbow. (By using another prism, he put the colors back together again to make white light, clearing showing that the colors were in the light, not the prism.) Lenses had been used for centuries to bend light in ways that would enlarge or shrink images. Telescopes and microscopes had been in use for well over a century by Maxwell's time. More recently, new discoveries had been made about polarized light.

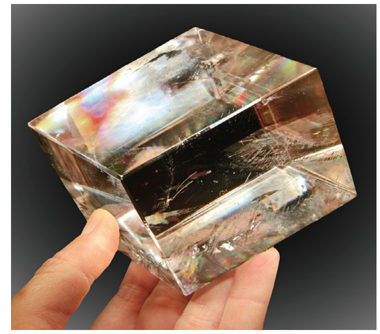
James knew that when light was reflected off a surface, such as a piece of glass, the reflected rays of light change and do strange things. When polarized light was used to look at certain things, beautiful swirly color patterns would be produced. Exactly why this happened was unknown, and James wanted to learn whatever he could about polarized light. He remembered the large pieces of Iceland spar (a clear mineral) that he had seen in the collection of one of his professors but knew there was no way he could afford to buy any like those. Instead, he tried gluing pieces of glass inside a matchbox. He also got pieces of a much less expensive mineral (mica) and spent hours slicing and polishing them.

He had quite a bit of success even with these less-than-perfect polarizers. He looked a melted glass through his polarizers and realized that the colored rings he was seeing weren't just pretty patterns, they were actually showing him something important. Those colored lines showed him where the stressed areas in the material were. To test this theory, he knew he should use a material that could be stressed right while he was watching it under the polarizers. He could apply stress and watch where rings and lines appeared. He needed something that light would go through but that was also soft enough to bend and stretch. He decided to head to the kitchen and cook up a batch of clear jelly.



He made a ring of jelly with a cork stuck in the center hole. He would twist the cork to put stress on the jelly but not actually tear it. (Imagine someone putting a cork in your belly button then twisting it a bit. Ouch! That was what James was doing to the jelly ring. There was a colored ring or line in the places that were going "ouch.")

He even found a way to record the things that we was seeing. He made a simple device called a camera lucida, that projected the image of what he was seeing onto a piece of paper. He would then use watercolor paints to trace the image onto the paper. He sent some of his watercolors to an artist he knew who was also very interested in polarized light. The artist was so impressed with James' work that he sent him two large specimens of Icelandic spar. These mineral specimens became some of James' most treasured possessions.


A very nice specimen of Icelandic spar

The long holidays from school also gave James opportunities to spend time thinking about geometry problems. He became interested in cycloids, the line patterns you get when you roll one circle around another. For example, if you put a dot on a bicycle wheel, then follow the dot as the bicycle rolls along, you get a line that looks like series of half circles. We wrote a paper about the equations he had come up with to describe these shapes, and it was presented at a meeting of the Royal Society. He was getting very good at using math to describe things. He even found a way to use math to describe the colorful patterns that he saw in the jellies when he put them under the polarized light. He wrote up another paper for the Royal Society. This time, however, he was sloppy in his writing and his professor, James Forbes, told him to rewrite it because he was capable of much better. James never forgot this hard lesson and from that time on he took the time to carefully edit his papers.

Eventually, James' father realized that James wasn't going to be a lawyer. Any young man who can have three mathematics papers presented to the Royal Society before he turned 20 deserved to have an opportunity to study math and science at a world-famous university. Therefore, it was arranged for James to attend Cambridge University, north of London, England. Cambridge had produced many fine mathematicians and scientists, including Isaac Newton, Francis Bacon, William Harvey, Charles Babbage and Henry Cavendish. The name James Clerk Maxwell would soon be added to that list.

The schedule at Cambridge was more intense than anything he had experienced before. His classes really kept him busy and he found it difficult to accomplish everything he wanted to do. Sometimes he had to do things at odd times of the day. For example, he tried jogging after he finished his studies at about 2:00 AM. His dormitory had two floors and a staircase at either end and he would use them as a running track. The students who lived in the rooms off these hallways were less than pleased to have someone running past their room every few minutes in the middle of the night. So they would hide behind their doors with objects like boots and brushes and throw these at him as he went past. James got the hint and decided maybe he should change his schedule a bit.

Soon after he arrived at Cambridge (in the section called Trinity College) he accepted an invitation to join an exclusive club called the Selective Essay Club. There were only 12 people at a time in this club, and because of this they sometimes called themselves The Apostles Club. They would take turns reading essays they had written and then discussion and debate them. James loved to think and write about philosophical issues, not just mathematics, so this gave him an opportunity to do so. In one essay, called "Is Autobiography Possible?" he states his belief that no one should reveal to the public the private details of their life. (What would James think of Facebook and Twitter?!)

James missed all the animals back at Glenlair, especially the dogs. There were some cats in the building where he lived, probably kept to keep the rodent population down, so James befriended them and allowed them to come in his room. Some sources say that he did experiments on them, dropping them from various heights to see if the landed on their feet.

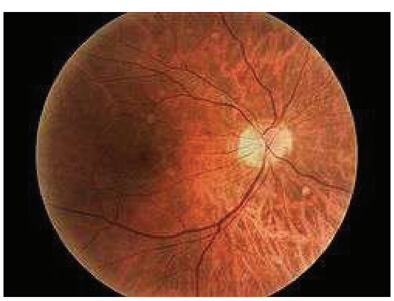
Because James spent so much time studying while at Cambridge, he didn't have time to do many of his own investigations. Besides all the regular exams, James also entered some very tough competitions. The most difficult one lasted seven days! James was really good at math, but there was actually a student in his class who was a little bit better than he was, so James came in second in the math exam. Second was very good, though, and he came in first in another category. He did so well, in fact, that Cambridge gave him an offer to stay on as part of their staff, teaching the beginning students. After a few years, he would then be qualified to apply for a job as a professor at any university he chose.

Even though James had been very busy with his own studies, he had always found time to help others. We know that he once helped a friend who had eye trouble by reading the lessons to him. He visited friends who were sick and tried to cheer up those who were discouraged. He helped first-year students who were struggling and needed tutoring help. Someone who knew James during his days at Cambridge said this about him: "He was friendly and kind. Everyone who knew him can recall some kindness or some act of his which left a permanent impression of his goodness on their memory, for Maxwell was "good" in the best sense of that word."

The River Cam next to Cambridge

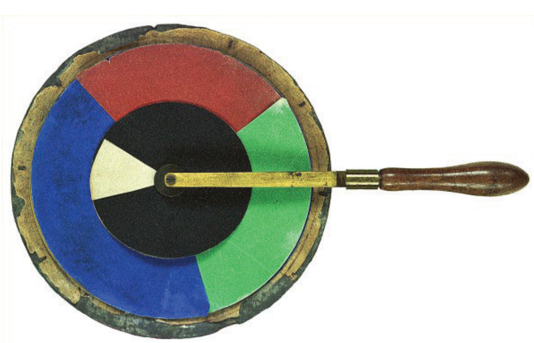
After graduation, James had more time to spend on his own experiments. He did have teaching duties, but evenings and weekends allowed plenty of time to continue his scientific interests. In addition to his teaching and experimenting, he also spent more time exercising. He would go on hikes, swim or row boats in the Cam river, or work out in the new gym on campus. He even helped to organize a swimming club.

James found himself thinking a lot about light and color. He'd been thinking about color ever since he was a toddler, when he would ask people why the sky was blue and no one could give him a satisfying explanation. Other things puzzled him as an adult. Everyone knew that sunlight contained all the colors of the rainbow, but what about the colors brown and gray? They weren't in the color spectrum. Did light combine in the same way that paints can combine? Artists mix blue and yellow paint to make green paint. Did that mean that yellow light and blue light make green light? And what role did the eye play in seeing light? Very little was known about the inside of the eye.



James decided to learn everything he could about eyes. He made a device that would allow him to look inside an eye. He had a very hard time convincing anyone to let him stare at their eyes, so he started by using a mirror to look in his own eye. Then he realized that animal eyes were very much like human eyes, and he knew several dogs in the area. The dogs might have been shy or squirmy at first, but James was an excellent dog trainer and after a few lessons and some yummy treats, the dogs would allow him to stare into their eyes and make observations. James wrote about what he saw in dog eyes: "They are very beautiful, with glorious bright patches and networks of blue, yellow and green, with blood vessels great and small."

Finally, he found a few people who trusted him enough to let him use his tool to look at the back of their eyes. He thought that human eyes were not nearly as beautiful as dog eyes, but humans could use words to tell you what they were seeing, and that was helpful sometimes. He saw that the back of the eye, the retina, was fairly dark, with a small yellowish spot near the center. In this picture, the yellow spot is the optic disc, the place where nerves and blood vessels come into the eye. What James did not know is that this optic disc creates a "blind spot" in our vision. We don't notice this blind spot because our brain fills in the missing details.



At the same time, James decided to begin experimenting with color. He remembered an experiment that Professor Forbes had done, putting colors onto a spinning top. Prof. Forbes had explained that the colors spin so quickly that the eye can't react to each individual color but combines them into one color. So James made his own version of this spinning experiment. The wheel shown here is a photograph of the actual wheel that Maxwell made. However, before we go on, we need to give credit where credit is due, because Professor Forbes' ideas about light and color came directly from someone else's work.

Thomas Young

Professor Forbes had read about the theories and experiments of Thomas Young. Young was still alive while Professor Forbes was growing up, but had died two years before James was born. Interestingly, James and Thomas shared their birth date, June 13. They also shared the trait of being interested in a lot of topics, and being good at just about anything they set their mind to. By the age of 14 Thomas knew Latin and Greek and was familiar with many other languages as well, such as Hebrew, Arabic Turkish and Persian. Later in life he would study Egyptian hieroglyphic writing and help to decipher the famous Rosetta Stone.

Like James, Thomas studied at both Edinburgh and Cambridge, although he went other places, too. Unlike James, his university degree was in medicine, so his daily job was being a doctor. In his spare time he studied other things, such as languages, math, music and the science of light. On the basis of his experiments comparing water ripples to light ripples, Young had concluded that light must be a wave, not individual particles. This contradicted the writings of many scientists including Isaac Newton. Newton believed that light was made of invisible particles that moved very fast. Most scientists of Thomas Young's day agreed with Newton. In the end both turned out to be correct, as light is both a wave and a particle.

James Maxwell with his color wheel

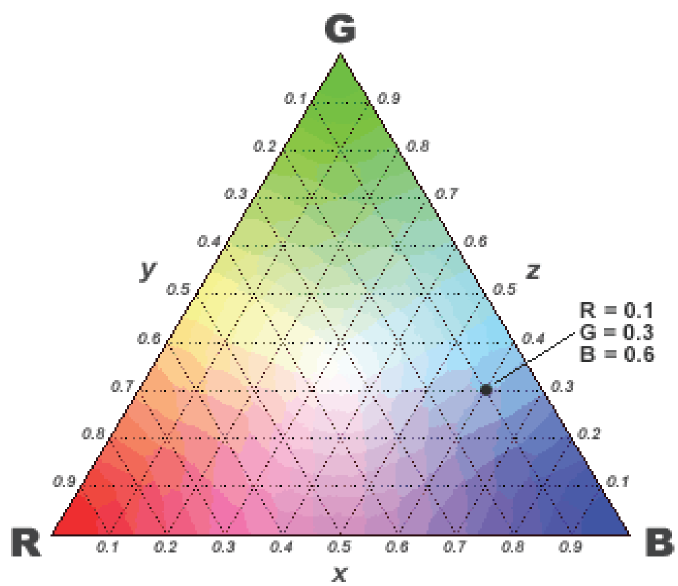
Like James, Thomas was interested not only in light itself, but also in the eye as the receiver of light. Thomas believed that the eye had only three basic color receptors; all other colors were the result of how the eye and the brain perceived mixtures of these three. He turned out to be right, but how he came up with the number three is unknown.

James decided to pick up where Thomas had left off and try to figure out the nature of those three receptors. He made three paper disks: red, blue and yellow. He knew these were the "primary" colors that artists used. He knew that blue and yellow paint can be mixed to make green, so he made his wheel half blue and half yellow and gave it a spin. What he saw on the spinning disk was not green, but pink. This was a surprising result. He tried other color combinations, but nothing came out the way he expected. Red, blue and yellow must not be the primary colors of the eye.

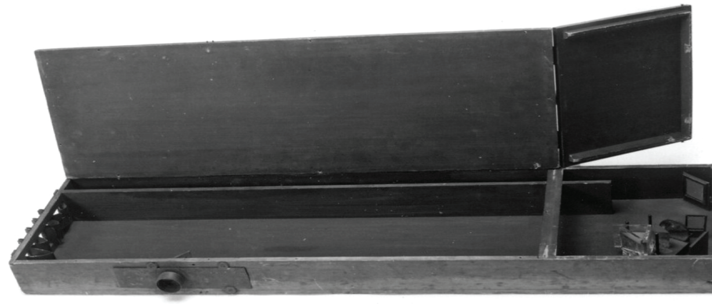
He began experimenting with other sets of three colors, and when he tried red, green and blue, something amazing happened. Spinning these three colors made them look very close to white. He then assumed that the eye must have red, green and blue receptors.

The next step was to make a chart of what you got when you mixed various proportions of each color. His paper disks could be adjusted so that more or less of each color would be shown. The percentages were carefully recorded on each side, so it was a very mathematical approach to describing color.

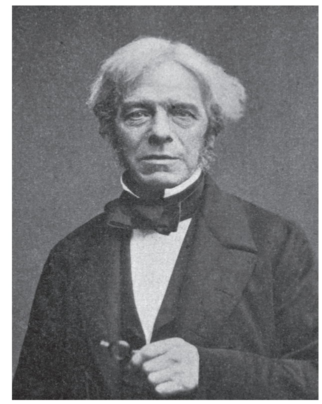
Then James thought of a possible problem— how could he be sure that his choices for color matches between color wheel and the paper samples were correct? What if each person saw colors differently? Perhaps this triangle was just his own perception. So he asked many friends to come to his lab to try out the color wheel. What he found was that most people seemed to see colors exactly the way he did. After looking at the spinning wheel, they would pick out exactly the same paper sample. The only exception was people who were known to be color blind. Interestingly, not all color blind people would make the same mistakes in matching. There seemed to be different types of color blindness. James guessed that it was because people could have a problem with just one receptor. Most of his color blind volunteers seemed to be missing the red receptor and could not tell red from green.



Most people would stop there, satisfied that they had solved the mystery of color. But not James. He realized that he needed to experiment with light itself, not just colored paper. He used several prisms inside a wooden box to separate light into its spectrum colors. He put slits in the box so that he could let just one color come out of the box. Now he had a source of color directly from light. The box was fairly large, and took up most of the space on any table it sat on.



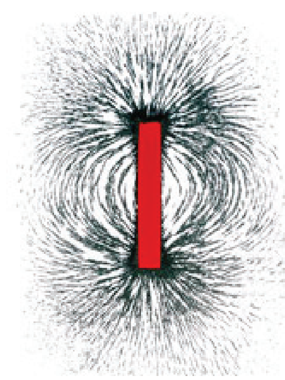
James would continue to experiment with the light box for many years. (After he got married his wife would even help with the research.) Meanwhile, James was also spending a few hours a day reading books about electricity and magnetism. He read about all the theories and experiments that had taken place in past years. It seemed that scientists were divided in their views about magnetism. Some held that when magnets pull on a metal object, they are doing so “at a distance,” meaning that nothing is happening in the space in between. This seemed to be the way gravity works, so maybe magnetism was the same. The other view was that something was indeed happening in that empty space between magnet and metal. Michael Faraday was the main advocate for this theory. He claimed that the space all around a magnet was filled with invisible lines of force. His experiments had shown him that magnetism and electricity were linked somehow. He had made electricity using magnets, and could make magnets using electricity. He called this “electromagnetism.” Many scientists of that day scoffed at Faraday’s ideas. Faraday had been born into a poor family and had never studied at a university. How could he know more than they did? Impossible!



Michael Faraday

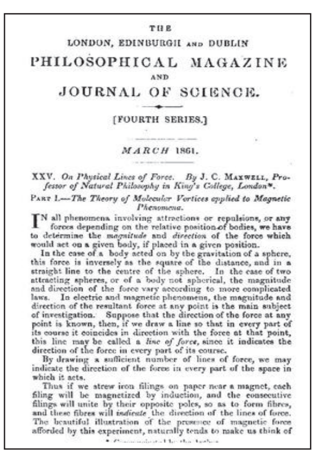
As James read Faraday’s writings, he followed along with each experiment, and imagined in his mind exactly what Faraday had seen. He marveled at Faraday’s excellent experimental techniques. Faraday wrote about his failed experiments, not just his successes, and James admired that. James was convinced that Faraday was right. What Faraday lacked was the mathematical equations to back up his theory. Perhaps James could help, since he seemed to be good at using math to explain things.

This picture shows bits of iron that were sprinkled around a red magnet. The tiny pieces of iron are lined up along Faraday’s invisible lines of force. Faraday had imagined these lines as “tentacles” wrapping around the outside, from pole to pole. James decided to think of them not as tentacles but as a steady stream of fluid and decided to use the word “flux” to describe them. The more dense the flux was at a certain point (at the poles, for example) the stronger the electric or magnetic force at that point. James guessed perhaps this flux worked like the water in the streams at his home in Glenlair. In places where the stream was narrow, the water ran faster and harder. In places where the stream was wide, the current slowed down and was more gentle. What if electromagnetic flux worked like this?



Tiny bits of iron can show the fields around a magnet.

James thought about other ways that fluids behave. Water flows from high areas, like mountains, to lower areas, like valleys. When it reaches the lowest point, such as a pond, it stops flowing and sits there. What makes fluids move is a difference in height or in pressure. Fluids always want to escape high pressure and move to areas of lower pressure.



THE
LONDON, EDINBURGH AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.
[FOURTH SERIES.]
MARCH 1861.

XXV. *On Physical Lines of Force.* *By* J. C. MAXWELL, *Professor of Natural Philosophy in King's College, London**.

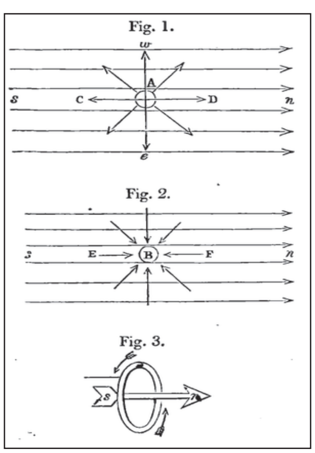
PART I.—*The Theory of Molecular Vortices applied to Magnetic Phenomena.*

IN all phenomena involving attractions or repulsions, or any forces depending on the relative position of bodies, we have to determine the *magnitude* and *direction* of the force which would act on a given body, if placed in a given position.

In the case of a body acted on by the gravitation of a sphere, this force is inversely as the square of the distance, and in a straight line to the centre of the sphere. In the case of two attracting spheres, or of a body not spherical, the magnitude and direction of the force vary according to more complicated laws. In electric and magnetic phenomena, the magnitude and direction of the resultant force at any point is the main subject of investigation. Suppose that the direction of the force at any point is known, then, if we draw a line so that in every part of its course it coincides in direction with the force at that point, this line may be called a *line of force*, since it indicates the direction of the force in every part of its course.

By drawing a sufficient number of lines of force, we may indicate the direction of the force in every part of the space in which it acts.

Thus if we strew iron filings on paper near a magnet, each filing will be magnetized by induction, and the consecutive filings will unite by their opposite poles, so as to form fibres, and these fibres will *indicate* the direction of the lines of force. The beautiful illustration of the presence of magnetic force afforded by this experiment, naturally tends to make us think of



The best thing about this fluid analogy was that there were already equations about fluids. He could start with those equations, and then somehow adapt them to his electromagnetic flux idea. He eventually came up with equations that seemed to describe exactly what Faraday had found in his experiments. He wrote a paper about his discoveries and called it: “On Faraday’s Lines of Force.” Michael Faraday was amazed when he received a copy of the paper. Someone had proven his theories!

Here on the left, you see the cover of his published paper, plus one of the illustrations. Notice that the word “science” is used. Previously, science had always been “natural philosophy.”

3

During this period of time when James was working on color theory and electromagnetism, he was also keeping up with his full time job as a teacher. Students loved his classes because he would go to a lot of trouble to set up interesting hands-on demonstrations. (Once when he was lecturing about how to calculate the rate at which water would escape from a hole, a pipe burst on campus and produced exactly the effect he was teaching about!) James wanted everyone to learn, not just the gifted and wealthy students that came to Cambridge. He helped to set up a Working Men's College that provided evening classes to ordinary folks who wanted more education. He didn't think he was above this kind of teaching and even did many lectures himself.

A Working Men's College in London

During the school vacations he would go home to Glenlair and help his father manage the house and farms. He did ordinary jobs like fixing machinery, paying bills, and caring for animals. During one of these vacations he was introduced to a younger cousin, Lizzie, and the two fell in love. The older relatives in the family said that although there wasn't a law saying that cousins couldn't marry, they thought it was unhealthy and would not allow James and Lizzie to continue their relationship. After a normal amount of heartbreak, both of them moved on with their lives and eventually married other people. It would not be too long until James would meet his future wife.

One day, James got a letter from Professor Forbes, back in Edinburgh. He told James that there was a job opening at a smaller college in the city of Aberdeen, the largest city in the north of Scotland. The college was looking for a natural philospհy professor and they were willing to consider younger men, not just older ones. James' father wanted him to apply for the job because Aberdeen was closer to Glenlair than Cambridge was. James did apply but did not get an answer right away. Not long after this, his father got very sick with a lung infection. Back in that day there were no antibiotics, and people often did not recover from infections. James left Cambridge and went home to take care of this father. He joked with his friends that he had turned into a nurse. One day a letter came, telling James that he could have the job at Aberdeen if he wanted it. His father was very happy and had a few weeks where he felt much better. But the infection came back and one morning he died quite suddenly. James was now the master, or "laird," of Glenlair, a responsibilty he took very seriously. He decided to take the job in Aberbeen, but not before he had made sure that all the farmers and workers at Glenlair knew how to run the estate by themeselves when he was away.

James arrived in Aberdeen to take his job as a professor when he was 25 years old. The other professors were very nice to him and often invited him to dinner. The only thing he could complain about was that no one liked to tell jokes. They were all their 50s and 60s and didn't need to tease and joke around like younger men did. James wrote this in a letter to a friend, "No jokes of any kind are understood here. I have not made one for two months, and if I feel one coming on I shall bite my tongue."

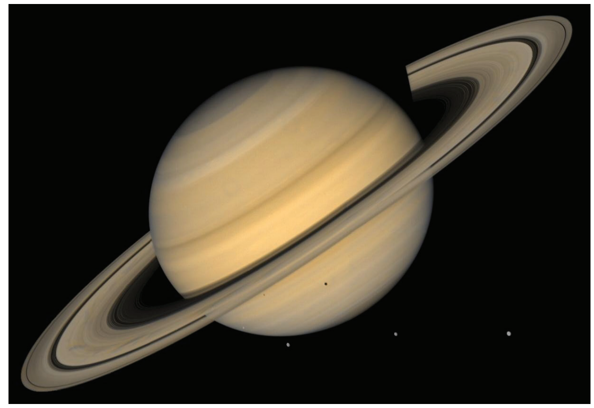
The other professors wanted to know what kind of teacher James would be, and they asked him to give an introductory speech about his teaching philosophy. He opened his speech by saying that he didn't want to simply teach science, but rather to use science to teach students to think for themselves. He also told everyone that experiments and demonstrations would be a key part of his teaching. One of his first lessons was on optics and he even bought fish and cow eyes for the students to dissect.

Marischal College in Aberdeen, Scotland

the River Dee, near Aberdeen

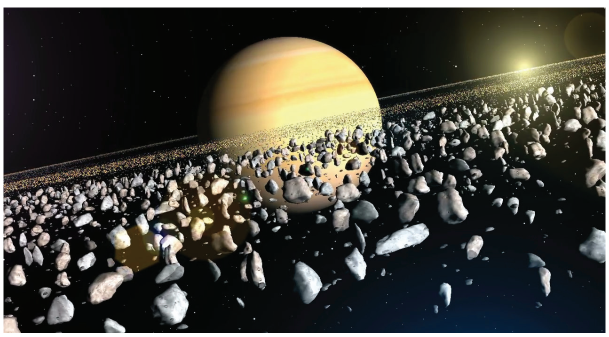
There was a river near the college, but it was nothing like the Cam River. It wasn't good for swimming and boating. Walking was just about the only option he had for exercise.

During that first year of teaching at Aberdeen, James heard about a contest that Cambridge University was sponsoring. They were giving a prize to anyone who could figure out what the rings of Saturn were made of. Astronomers had known about Saturn's rings for quite some time, but they did not know whether they were solid, liquid, or made of tiny particles. James began to think about Saturn's rings and how he might use math to solve the puzzle.



First, he read some math books and found some equations that he thought might be helpful. These were standard equations that everyone knew about, intended to be used to figure out problems involving water. James decided that the equations should work here, even without water. He found that if Saturn's rings were made of one solid piece and were very even all the way through, the constant rotation around the planet would eventually cause the ring to break apart. The only way a solid ring could be stable was if most of the mass was all clumped together in one place on the outside of the ring. Everyone know this was not true because they could see in their telescopes that the ring was very thin all the way around and did not contain any huge blobs.

Next, he thought about what would happen if the rings were made of a fluid. He used equations by a famous mathematician named Fourier to show that the fluid would ripple about, and the waves would eventually cause the ring to break up into separate blobs. Again, astronomers could see Saturn well enough to know that the rings were not made of several large blobs.

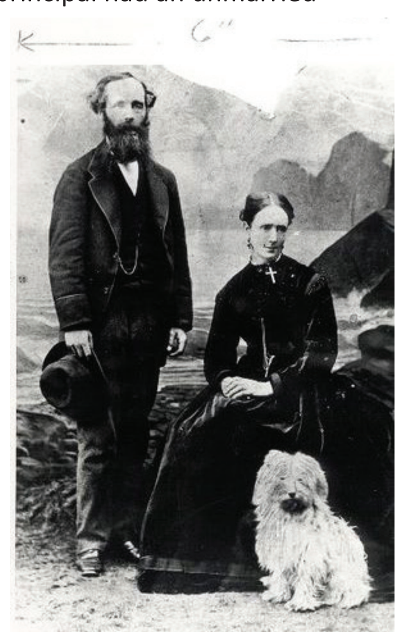


In the 1980s, satellites Voyager 1 and 2 flew past Saturn and took pictures of the rings. They are, indeed, made of particles. This is a computer image showing what the particles might look like.

Finally, he studied the possibility that the rings were made of many small particles. It was impossible to calculate what would happen to every particle, so he just imagined a small single ring made of equally spaced particles. The math equations showed that a ring like this would vibrate in four ways, but as long as the ring was not too dense in comparison with Saturn's density, it would be okay. Since the other two possibilities (solid and fluid) did not work at all, the rings must be made of many tiny particles.

James wrote a paper about his findings and sent it to Cambridge. No one else had even entered the contest, so James was declared the winner of the prize. When physicists around the world read his paper and saw how he had used those math equations, they were very impressed. James wasn't just a number cruncher. His thinking showed great creativity.

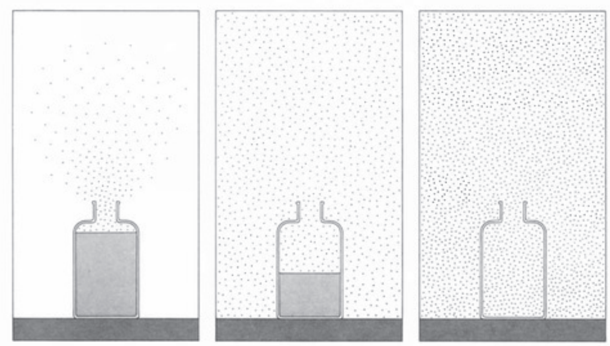
During this time, the other professors continued to invite James into their homes for dinner, but the home he visited most often was that of the principle of the college. It just so happened that the principal had an unmarried daughter 7 years older than James, and the two of them got along very well together. Perhaps at first, it reminded James of spending time with his cousin Jemima, who was also 7 years old than him. Eventually, James and Kathryn decided that they wanted to spend the rest of their lives together. James wrote a poem for Kathryn, asking her to join him at Glenlair. Here are a few lines from the poem. ("Ain" means "our," "bonny" means "beautiful," "braes" means "hillside," and "burnside" refers to Glenlair.)



Will you come along with me, in the fresh spring tide,
My comforter to be, through the world so wide?
Will you come and learn the ways, a student spends his days,
On the bonny bonny braes, of our ain burnside?

In June of 1858 they were married, with James' best friend from childhood, Lewis Campbell, as their best man. Kathryn would turn out to be a very good companion, indeed, and would help James with many of his experiments. This picture shows them with their dog, Toby. From that time on, James was never without a dog named Toby at his side. (When the current Toby died, he would get a new Toby.)

James had not yet published anything about his work with red, green and blue light. Now was the time to finish that up so he could move on to other things. A craftsman in Aberdeen made him an improved light box that gave better control of the proportions of colors, and Kathryn helped to make all the final observations. The research paper was written and published, and then James felt free to explore other topics. He would eventually get back to the topic that made him most famous, electricity and magnetism, but first something else caught his attention.



In 1859 he read a paper by a German physicist who was puzzling over how gases are diffused into air. For example, if a perfume bottle is opened in one corner of a room, the smell will gradually travel farther and farther way from the bottle until eventually the whole room is filled with the smell. Scientists were already pretty sure that gases consisted of very small particles, and that these particles likely collided with each other as they went through the air. These collisions between the molecules would help to spread them out. What puzzled this German scientist is that the math equations he was using predicted that the gas molecules would have to travel at an enormously high speed. If they were traveling this fast, the smell of a gas should spread much faster than it actually does in a real situation. What was going on? James became fascinated with this problem and decided to see if he could solve it.

Back at Edinburgh, James had been taught that the pressure of gases was caused by the repulsion of the particles (which we now call molecules). This would be a bit like the repulsion that two north poles of a magnet have for each other. The gas theory stated that the gas particles repelled each other for some unknown reason. To James, this didn't make sense. He preferred the other theory of gases, the kinetic theory. ("Kinetic" means "moving.") This theory stated that gas particles are in constant motion. If the gas is heated, they speed up, and if they are cooled, they slow down. As the particles move, they bump into each other. This can change the direction in which they are traveling, but is a random process with particles having an equal chance of going in any direction. James could not explain in words why he thought the kinetic theory was right. He just knew it was. This is called "intuition" and James had a lot of it.

Once again, the solution to the problem was to be creative. Everyone else had tried to solve the problem by thinking about all the individual particles. James thought it might be okay to simply consider the volume of gas as a whole, and think about what this entire volume might do. Again, he used math equations that were already in existence, but applied them in a way no one had thought of. He borrowed equations from a branch of math called "statistics." This is the branch of math that tells you how likely something is to occur. For the first time ever, James created a set of statistical equations that applied to gases. Once he had done it, everyone thought to themselves, "Now why didn't I think of that?" Other physicists and chemists picked up this idea and ran with it, and today we have a whole branch of science called statistical mechanics.

Ludwig Boltzmann

James was extremely clever, but he was not perfect. As he continued to work on more theories of gases, he began to make mistakes. He made an incorrect prediction about what would happen to the thickness of gases as temperature increased. Experiments proved him wrong. He also made calculation errors in his equations about the nature of the energy in gases, mainly because he forgot to convert kilograms to pounds, and hours to seconds!

James went on to other things eventually, and his ideas about gases were taken up by another man, Ludwig Boltzmann from Austria. Boltzmann spent most of his life studying this kind of science, but some of the discoveries bear both men's names, most famously the "Maxwell-Boltzmann distribution of molecular energies."

As usual, James was doing all this research in his spare time. His full-time job was still teaching classes. We have quite a few firsthand accounts of what James was like as a teacher. His brain was always full of pictures of what he was thinking, so he used a lot of picture analogies when he was teaching. (For instance, electricity is like water.) This was okay to a point, but sometimes he would switch to different picture images so many times in one lecture that the students found it confusing rather than helpful. James would also make arithmetic mistakes on the blackboard and, if the math was very complicated, end up wasting lecture time trying to track down his mistake. What the students liked best about his teaching was his enthusiasm and the way he cared about his students. He would often spend hours talking with small groups after class, and would use his own library privileges to check out books for them.

James also continued doing evening lectures at the local Working Men's College. One man who went to those lectures later wrote about them. He particularly remembered the time that Prof. Maxwell brought a machine to class that would generate static electricity. He would ask for a volunteer to stand on an insulating mat, then apply so much static to them that all their hairs stood on end. Today, this is not an uncommon site at a hands-on science center, but back then this was quite an exotic experience! (This picture shows someone touching a Van de Graaff generator at a science museum.)

Big changes were about to take place in Aberdeen. The colleges had decided to combine to make one large university. This meant that some professors would lose their jobs. The University of Aberdeen would need only one head of the natural philosophy (science) department, and James was by far the youngest and least experienced person applying for the job. It was not a surprise when James was told he had to leave Aberdeen and look for a teaching job at another university. Professor Forbes was retiring, so James applied to be his successor. No luck. His old school mate, P. G. Tait got the job. Then another opportunity came up at King's College in London, and this time James was selected.

a bay pony

This is how the Maxwell's Kensington house looks today.

James returned to Glenlair for the summer, knowing that in the fall he would be moving to London. He wanted to make the summer special for Kathryn, so they went to a horse fair and bought her a bay pony. Unfortunately, the pony was not the only thing they brought back from the fair. They were exposed to the viral disease called small pox, and James came down with it. Small pox often killed people. In the 1900s, vaccines were developed to prevent pox viruses from spreading, but in the 1800s they were still a major threat. James became very ill for several weeks as his body struggled to fight the virus. Kathryn was at his side doing everything she could to help him through. Eventually, his body won the battle and he began to recover. Once he was well enough to be outside again, he devoted many days to training the pony, which they had named Charlie.

James and Kathryn took Charlie with them when the moved to London. They rented a house in the neighborhood called Kensington. Nowadays, Kensington doesn't have horse stables, but back then they were able to rent a stable for Charlie so Kathryn would be able to go out riding any day that the weather was nice. James often rented a horse for the afternoon so they could ride together.

James was expected to introduce himself to the college with an inaugural lecture. At age 29, he had already given several of these, so he used the same themes that he had before, stressing the importance of helping students to think for themselves. He said, "I know the tendency of the human mind is to do anything rather than think. But without understanding the principles on which formulas depend, the formulas themselves are mere rubbish." He also wanted to include his own opinion about scientific discovery. At this point in time, some were beginning to complain that pretty much everything about science had been discovered, and there was very little left for newcomers to do. James said, "The present generation has no right to complain about the great discoveries already made., as if they leave no room for further enterprise. These discoveries have only given science a wider boundary."

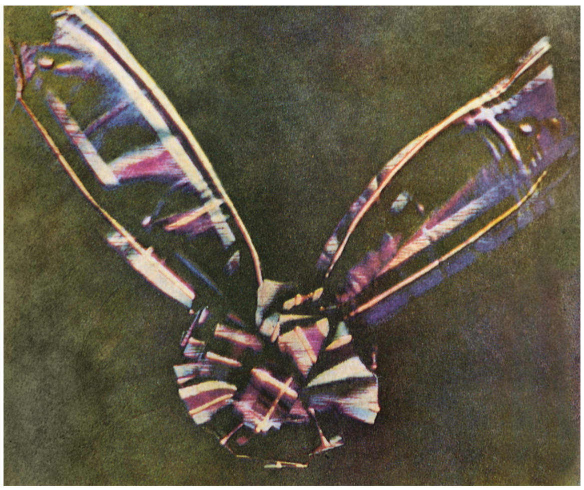
Living in London gave James a new opportunity he had never had before— attending lectures at the Royal Institution, the very place where Michael Faraday had presented his lectures about electromagnetism.

King's College, London, as it looks today. The object in the middle of the skyline is a ferris wheel called the London Eye. None of these tall structures were there in Maxwell's day.

Faraday was elderly by now and rarely gave lectures, but he did attend some, and thus it was that James Maxwell met Michael Faraday in person. They had corresponded by letter for several years, so both men were very excited to meet the other in person. They felt like a team, in some respect. This would give James' renewed interest in electromagnetism and get him back to researching this topic. But first, he had return to the topic of color vision one last time because the Royal Institution had asked him to give a lecture about it.

James wanted the lecture to start with a dramatic demonstration showing how red, green and blue light can combine to make any color. He could not demonstrate his light box because it could only be used by one person at a time. He had a spinning top, but that was still no good because people at the back of the auditorium would never be able to see it. What he needed was something large and colorful that everyone could see. He hit upon the perfect idea— he would make the world's first color photograph and project it onto a screen for everyone to see. A friend of his was an expert at making photographs, which at this time was a complex process involving glass or metal plates that had to be developed using chemicals. But these photographs would only be black and white. Where would the color come from?

James' idea was to take three separate photographs of the same object, but put a colored filter over the lens each time. The photographs produced would still be black and white, if they were all projected onto a screen at once, and if those same color filters were put in front of the corresponding projectors, the result should be to produce a color picture of the object.



Now here is where luck stepped in. James had a tartan ribbon that he thought might look nice in color. What he didn't know was that this ribbon had some unique features that would allow his idea to work, even though his theory was not perfect. He was indeed able to produce a color image of the ribbon using the technique he had planned. The actual image is shown here on the left. The audience that night at the Royal Society was stunned. No one had ever seen a colored photograph. Immediately, other scientists tried this new technique, but no one could get it to work. Photographic plates seemed not to be sensitive to red light. The red part of an image would always be missing. How had James gotten those pink colors in his ribbon?

Photographers puzzled over this for more than 100 years, trying to figure out how he had done it. Finally, some researchers at Kodak solved the mystery. The makers of that particular ribbon had used a red dye that also contained a chemical that gave off ultraviolet light. It was the UV light that the plate had picked up, not the red. Not only that, but one of the chemicals used to develop the picture just happened to be sensitive to UV light. If this had not been true, the plate would not have shown the UV image,. It was an amazing coincidence. The result was so impressive that James was immediately elected as a member of the Royal Society. (His work on the rings of Saturn also played a part in his election.)

Finally, James could go back to thinking about electricity and magnetism. Would he be able to remember what he was thinking five years ago when he wrote his first paper on this topic? Could he pick up where he left off and continue on? James was a believer in subconscious thought, the idea that our brains go on thinking about things at a very deep level even when we are not actively thinking about them. He wrote a short poem about this:

There are powers and thoughts within us, that we know not till they rise,
Through the stream of conscious action from where Self in secret lies.
But where will and sense are silent, by the thoughts that come and go,
We may trace the rocks and eddies in the hidden depths below.

James trusted that his brain would not only remember, but would come up with new ideas he had not thought of before. First, he clarified the problem. He needed to come up with some equations that could explain the following observable facts about electricity and magnetism:

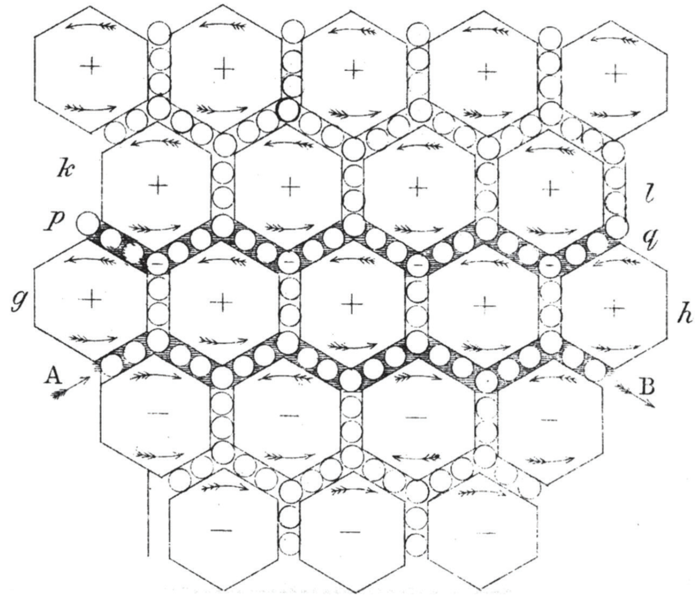
1) "Like" forces repel and "unlike" forces attract. These forces follow the "inverse square law" meaning that as the distance increases arithmetically (1 2, 3, 4, 5...) the force decreases geometrically (1, 1/4, 1/9, 1/16. 1/25...)

2) North and south poles always occur in pairs on a magnet. You never have north without south.

3) An electrical current in a wire creates a circular magnetic field around the wire.

4) A changing magnetic field produces an electric current.

James decided that he needed a better analogy. The analogy he had used previously, imagining electricity to be like water, had been a good place to start, but now it felt like a dead end. He needed something else. He began thinking about magnetic fields and how they go out at right angles to an electric current. How could this be represented? What if he imagined the space around the wire, the area of the magnetic field, to be filled with tiny rotating balls? He wasn't thinking about atoms. No, these were completely imaginary balls. He thought of them as "spinning cells." All they needed to do was explain why the magnetic field was at a right angle to the wire, not parallel to it. (In this case, the word "cell" is not referring to anything living, just an individual spinning unit.)



An illustration from Maxwell's finished publication about this topic. This diagram shows his "spinning cells."

He imagined that if the cells were all rotating in the same direction, they would exert a combined pushing force on anything in that space. The axes of the cells would be parallel to the wire. Perhaps these little cells bulged out a bit at their equators, like the Earth did? That bulge would be where the cells were actually touching and pushing on each other. If the balls were rotating in opposite directions that would cause problems, so he decided to imagine even smaller balls between them. Maybe he could even imagine these smaller "wheels" to be particles of electricity, and they exerted the force that set the larger balls spinning in one direction. He didn't need to explain it any more than that. He just needed the rough idea to work.

Furthermore, if he imagined that the lines of tiny balls were single lines of electrical current, he could extend them to wires outside of his spinning cell area, and by controlling the electrical particles, control the magnetic force created by the spinning balls.

If all of this sounds confusing, don't worry about it. The main point is to understand that James was cleverly drawing upon his knowledge of how real gears and balls work and applying this knowledge to an unknown situation. James went on to continue the analogy and found that it worked for all four of those observable facts listed on the previous page. (If you are intrigued and want to read more about the spinning cells in great detail, you can find this information in a book called "The Man Who Changed Everything" by Basil Mahon.)

The most exciting thing about this analogy from James' point of view was that he might be able to use it to make predictions about things yet to be discovered. For example, according to his spinning wheels model, electricity and magnetism are permanently bound together and cannot be separated. They are the same thing, like two sides of one coin. Also, it seemed to him that there could be a tiny "twitch" in the system if something started to push on the wheels, but then they were stopped by the "friction" between them. Would this idea correlate to an observed phenomenon some day? Further, the energy movement in these spinning cells would act more like wave movement than anything else. Would electromagnetic waves behave like water or sound waves? His model predicted that this would be so. These would be questions for other scientists to investigate.


Maxwell during his early years at King's College

Right in the middle of all this work on the theory, the school term ended and James had to go home to Glenlair to take care of the estate. Oddly enough, he didn't take any math or science books home with him. He planned on spending the summer mending roofs and stone walls, taking walks along the creek and watching the northern lights on long summer evenings. As he was doing all this work, however, his brain kept thinking about the theory, and by the time he returned to London in the fall, he was ready to write up his theory and publish it.

James Clerk Maxwell

4

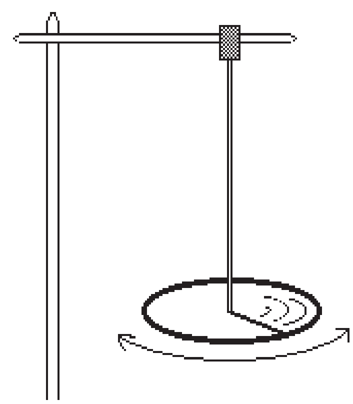
James and Katherine (with Toby, of course)

James returned to King's College in the fall, not just ready to begin a new semester of teaching, but ready to write and publish a new paper about electricity and magnetism. In this paper he introduced to the world his analogy of spinning cells and to the idea that light was a type of electromagnetic wave. It was a brilliant paper, but James was not entirely satisfied. His goal was to eventually understand electromagnetism well enough that he did not need the spinning cells analogy any-more. It would be two more years before he would reach this goal.

Meanwhile, James and Katherine continued to do more work with the light box. Every guest that came to their home was asked to look into the light box and describe the colors they saw. It was a tedious process, requiring many adjustments to the lenses and prisms, but eventually they collected enough information to be able to describe the difference in color vision between normal people and those who were color blind.

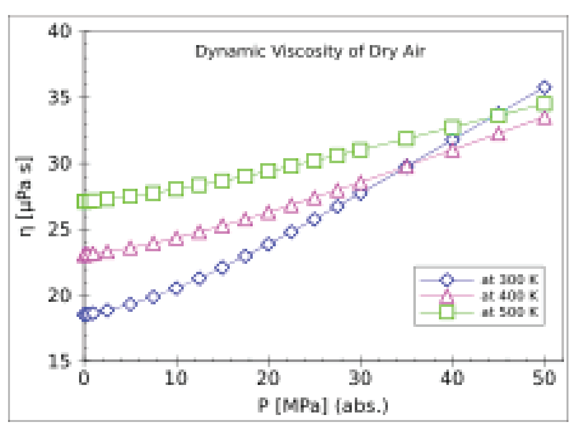
James also wanted to follow up on his theory about gases and run some experiments to see if his mathematical predictions were accurate. According to his equations, gases under pressure would not experience any change in their viscosity. "Viscosity" is a measure of how thick or how runny a substance is. For example, molasses and ketchup are very viscous *(viss-kuss)*. They are thick and run very slowly. Water and milk pour easily because they have a low viscosity. Honey is more viscous than water but not as viscous as molasses. We don't think of gases as being viscous at all, but they do have a small degree of viscosity. The problem was how to measure it. James came up with an ingenious invention to do just that.

The choice of which gas to use was obvious— regular air would be fine. It would need to be enclosed in a glass case that could be pressurized. To measure the viscosity, James used a type of pendulum that rotated around its axis, like a top, There were little "fins" mounted on the round, flat, plates of the pendulum, which would catch the air like the sail on a boat. If the air became more viscous as it was pressurized, it would slow down the rotation of the pendulum. It was a brilliant idea, but ended up being more difficult than he had expected. A number of things went wrong with the equipment and the glass case not only leaked but eventually exploded. James did not give up, and was ultimately able to get some good data. The experiments seemed to prove that James' equations were correct. Gases do not become more viscous as their pressure increases.



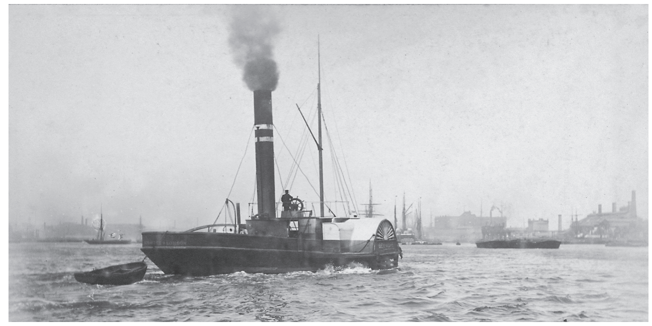
A torsional pendulum where the "bob" (weight) at the bottom spins instead of going back and forth.

Next, James wanted to see if this held true for increased temperature. He predicted that he would get the same results, and that increased temperature would not produce increased viscosity. For this experiment, the glass case would have to be wrapped in a metal lining that could be filled with hot water or with hot steam. Katherine was a great help in this experiment, carrying both boiling water and ice up to the attic. She wrapped the entire case in some old blankets to keep it insulated, and even put a feather cushion over the top. It's likely that they both watched the pendulum rotate, and made a precise count of how many rotations it made before coming to a stop. If the air was more viscous it would slow the pendulum down and cause it to come to a stop more quickly. They collected a lot of data, and when James analyzed it he discovered that his prediction was absolutely wrong! Gases did become more viscous as their temperature increased. James would have to do some re-thinking of his original theory. He did not have any immediate ideas, so he decided to let the question rest for a while and allow his subconscious mind to work on the problem while he was busy doing other things.



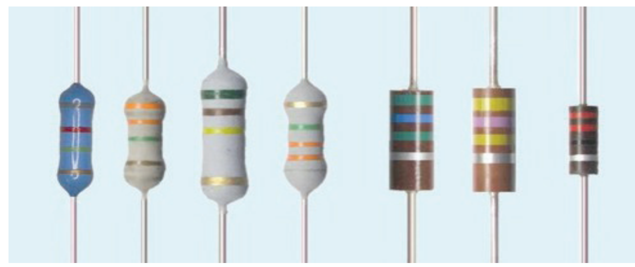
James' data might have looked something like this.

James was obliged to turn his attention to something that was not glamorous at all. In fact, many people would say it was downright boring. Scientists needed accurate ways to measure these new discoveries about electricity and magnetism. How can electromagnetic force be measured as it goes through a wire? James teamed up with some other scientists to create a complicated magnetic device that would hopefully measure the resistance of a wire to the electricity passing through it. Electrical resistance is a fundamental property of materials and would become an important property to measure. Their measuring device was an ingenious contraption that involved a spinning coil of wire that was sensitive to the earth's magnetic field. It needed to be very sensitive to give them the readings they needed, but they found that it was so sensitive that it could detect iron barges going up and down the Thames River nearby! They could only get accurate readings when no boats or barges were in sight. The last part of the experiment involved a precise measurement of the length of the wire they had wound into a coil. The unwound wire did not want to lie straight, so they had to take it to a university building that had wooden floors with wide cracks between the boards. They pushed the wire down into the long, straight cracks and were able to get the measurement they needed.

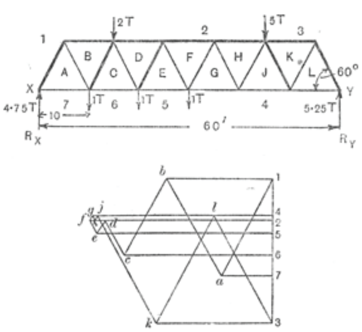


Iron steam boats like this were often seen on the Thames River during the years that James was at King's College, London.

They decided to create a new unit of measurement called the Ohm, named after Georg Ohm, who had come up with some mathematical laws to describe how electrical current flowed through wires. Ohms tell how resistant a material is to having electricity flow through it. If you want to reduce the flow of current coming into an appliance, you can use a resistor.



Resistors like these are used in many electronic devices today. The bands of color are codes that give information about the resistor, including how many Ohms it is.



As part of his teaching duties, James was required to keep up with all the latest technological developments in the world of physics and engineering. He read about the work of a Scottish civil engineer who had come up with a better way to build trusses (supports) on bridges. Some of his students were likely going to become civil engineers, so this was important information for them to know. However, James realized that there was a simpler way to do the math. Basically, he showed that you can use simple geometric drawings to represent a real structure. He quickly wrote up a paper about it, called "On Reciprocal Figures and Diagrams of Force." This led to several more papers, as his mind quickly jumped from one idea to the next. Today, these methods are common practice in the field of civil engineering, although computers have made the work much easier.

Finally, after this work was done, James was able to turn his attention back to his thoughts about the relationship between electricity and magnetism. Had his brain been working on the problem subconsciously all this time? Indeed it had, and in seemingly no time, he was ready to write a paper that would rock the scientific world. In a letter to his cousin, he expressed his feelings about his soon-to-be-published paper. "I also have a paper afloat, with an electromagnetic theory of light, which, till I am convinced to the contrary, I hold to be great guns." Great guns was an understatement. James knew he was on the brink of one of the most major scientific discoveries of all time. The equations that described his theory were shockingly simple (as far as physics equations go). This is what they look like:

These are known as "Maxwell's Equations" and are the foundation for the science of electromagnetism.

NOTE: The equations don't always look like this. If you do an image search online, you will find that there are several ways of writing these equations. The meaning, however, is always the same.

1) $\mathrm{div}\ \mathbf{E} = 0$

2) $\mathrm{div}\ \mathbf{H} = 0$

3) $\mathrm{curl}\ \mathbf{E} = -(1/c)\ d\mathbf{H}/dt$

4) $\mathrm{curl}\ \mathbf{H} = (1/c)\ d\mathbf{E}/dt$

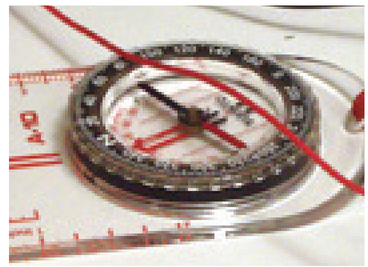
The paper was called:
"A Dynamical Theory of the Electromagnetic Field."

The year was 1864.

"E" stands for electrical force and "H" stands for magnetic force. They are written in bold (dark) letters to show that they are "vectors" which means they have direction as well as strength. The letters "div" stand for "divergence, and tells whether the force is directed outwards or inwards. The word "curl" means exactly that— something curls around something else. The terms "dH/dt" and "dE/dt" are rates of change over time. The letter "c" represents a number that James determined was necessary in order to make the equations work right. In James' mind, this letter "c" was like the tiny spheres in between the larger spheres in his spinning cell analogy. This is the same letter "c" that would appear in Einstein's famous "$e=mc^2$" equation several decades later. "C" has a numerical value: 300,000 kilometers per second (186,282 miles per second). Most of us know "c" as the speed of light. This number is especially important to astronomers, as we now measure the distance of stars in "light years."

So what do these equations mean? The first one says that there is no outward or inward electrical force around any single point. The second one says the same thing about magnetic force, and also implies that magnets will always have a pair of poles, north and south. (This is why if you break a magnet in half, both halves will then have north and south poles. Break those in half and your will get four magnets with north and south poles.)

The third equation says that when the magnetic force changes, it wraps a circular electrical force around itself. That minus sign means that the direction of the curling is counterclockwise. The fourth equation says that an electrical force will curl a magnetic force around itself in a clockwise direction as it travels. This explains the behavior of a compass near an electrical field. If you switch the direction that the electricity is traveling, the compass will spin around and point the other way (but still at a right angle to the wire). The third and fourth equations together tell us that electrical and magnetic waves always travel together and can't be separated. These waves are transverse waves, like the "up and down" waves we see in the ocean. However, in an electromagnetic wave, the electricity and the magnetism don't go up and down together, but at right angles to each other. Again, this helps to explain the behavior of a compass needle in the presence of an electrical wire. The compass needle goes off perpendicular to the wire. The theory also implied that electromagnetic waves could travel through empty space, not needing a "medium" travel through (like sound waves do).



How was the paper received? Was it immediately embraced by physicists everywhere? Hardly. It was more like stunned silence. These ideas were so new, no one knew what to think of them. If these waves really did exist, they must be everywhere, in an array of different wavelengths. So far, no scientist had ever claimed to have detected any of these waves (other than visible light, of course). It would be twenty years before anyone would claim to have discovered more forms of electromagnetic waves. During these twenty years, Maxwell's equations would remain just an interesting theory.

At the height of his career, James decided to leave King's College. We don't know exactly why, but it seems he felt a strong responsibility to his estate at Glenlair. He was the "laird" (Scottish for "lord") of the estate and it was hard to manage the estate while living in London. He resigned from his professorship and moved back home.

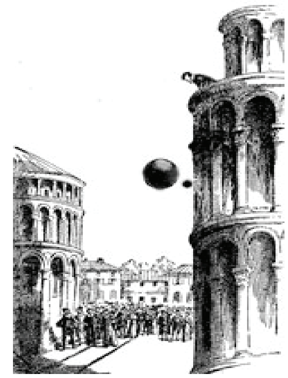
Back in Glenlair, James threw all his energies into upgrading many features of the estate, including a large addition to the house. His father had drawn up plans for this addition but had never had the funds to complete them. James brought his father's vision into reality. James also was interested in helping with building projects in his local community. He donated a substantial amount of money to the village church so they could build a house that could be occupied by whoever was the current minister.

Glenlair in 1884

James was also was concerned about the local school and donated some of Glenlair's property for a new school building. James and Katherine loved children and did what they could to improve the lives of all children in their surrounding area. One of the great sadnesses in their life was that they never had any children of their own. Nowadays, doctors can often correct reproductive problems, but back then there wasn't much that could be done. James always said that people should not sit around thinking about what might have been, but get busy and make the most of what they have. So he and Katherine never complained about their situation, but showered love and affection on all the children in and around Glenlair. James loved to amuse them with games and interesting tricks.

A friend wrote a description of James at about this time. He said that James had a strong sense of humor and a keen appreciation for witty conversation, though he would rarely laugh. You knew he was amused because of the twinkle in his eye. He was never boisterous or explosive, and never in a bad temperament. When other men would have been vexed and annoyed, James would remain infinitely patient and calm.

While the house was being renovated, James and Katherine decided to get out of the way of the workers and go on a long vacation. Neither of them had ever traveled much, so they decided to do a once-in-a-lifetime trip to Italy to see all the famous historical sites. The trip had some unexpected adventure added to it— the ship had to be quarantined when they got to Marseilles, France. That meant that no one was allowed to get on or off the ship for many days. This caused great distress among the passengers, and James volunteered to be in charge of the distribution of water on board. He spent many days hauling buckets of fresh water to passengers. When the finally got to Florence, Italy, who should they run into but James' best friend from childhood, Lewis Campbell! What an amazing coincidence. James and Katherine must have had a wonderful time visiting with Lewis and his wife.

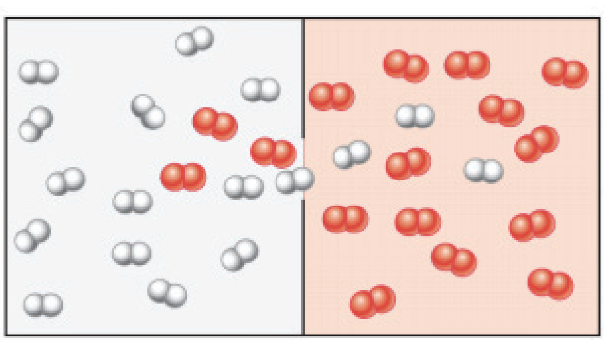

Galileo and the fallikng balls

James and Katherine took lessons in the Italian language while in Italy. James found it similar enough to French and German that he was able to catch on quickly. He was soon able to talk about scientific matters in Italian with some Italian physicists in the city of Pisa. Pisa is the city with the famous Leaning Tower, the building from which Galileo was said to have dropped the balls of different weights, proving that Aristotle was wrong when he said heavy objects fall faster.

James spent most of his time at Glenlair writing and re-writing various of his scientific papers. Publishing is a time-consuming process and James had to write all his papers himself since no one else understood what he was thinking. He also spent a lot of time writing letters to his colleagues at Cambridge, and to his friends P. G. Tait and William Thomson ("Lord Kelvin"). James continued to be a member of various scientific and mathematical societies and traveled to London occasionally to take part in their annual meetings.

James thought that a new textbook needed to be written about the science of heat, so he started writing one. He intended to simply write a useful textbook, but he ended up re-thinking the topic as he wrote. His publication, "The Theory of Heat," introduced new mathematical relationships between temperature, volume and pressure that are now known as Maxwell's relations. Maxwell's sense of humor really came out in this book. He used what is known as a "thought experiment" to discuss the idea of heat flow. Scientists had determined that heat always flows in one direction: from hot to cold. The flow of heat continues until "equilibrium" is reached, meaning that both the hot and cold areas are now the same temperature. This is what happens to a hot cup of coffee that sits on the table for a few hours. The coffee will eventually become the same temperature as the air around it. We all know that this situation will never reverse itself naturally. The coffee will never again be hot unless some energy is put back into it.

James had guessed that the temperature of a gas is related to the movement of its molecules. The faster the molecules are moving, the higher the temperature. He also guessed that not all the molecules would be moving at the same speed. As with any crowd, some are ahead of the game and some are lagging behind. On average, the molecules would be moving at a certain speed, but a few would be moving more slowly and a few would be moving faster. Just for fun, James invented a little imaginary character that would later become known as "Maxwell's demon." (The use of the word "demon" here does not imply anything evil. It might just as easily been called a "fairy" or an "elf.") This imaginary being was only slightly larger than the gas molecules themselves. The imaginary jar in which he lived was divided in half. Between the two halves was a wall with a tiny hole just large enough to let one molecule pass through. Over the hole was a little shutter that the "demon" could open and close. Every time a very slow moving molecule would come past he could open the shutter and let it escape into the other side. When a very fast-moving molecule came by he could open the shutter and let it pass through into the other side. The demon controlled the back-and-forth movements of the molecules so that all the slow molecules were eventually collected into one side and all the fast molecules into the other. Thus, the demon as able to make natural laws act in reverse. The jar would start out at equilibrium and end up with a hot side and a cold side! James then explained to his readers that information about gases is statistical, and describes only the behavior of the gas as a whole, not the individual molecules. Even the tiny demon would be unable to know enough about each molecule to be able to sort them.



Other things caught James' attention, too. He was outside a lot, walking across the Scottish countryside. He looked at all the hills and "dales" (valleys) and realized that there must be a relationship between them. He saw that the number of hills must always be one more than the number of dales. He came up with equations about this topic and published a paper called "On Hills and Dales." This branch of mathematics would eventually be called "topology."

What would turn out to be the final chapter in James' career began in 1871. Cambridge University felt like it was lagging far behind other universities when it came to scientific research. Many other universities, both in Britain and in Europe, were doing ground breaking experiments. Several financial donors volunteered to give Cambridge the money to build a state-of-the-art laboratory, which would be named after a brilliant (but rather odd) scientist named Henry Cavendish. (Henry's son, the current Duke of Cavendish, had been one of James' college friends.) Cavendish Laboratory would be looking for a director. Cambridge's first choice was James' friend William Thomson, who was working in his own lab in Glasgow, Scotland. Thomson turned them down. Second choice was Hermann Helmholtz of Germany, but he also declined. Third was James Clerk Maxwell, who took a long time to think about it, but eventually said he would take the job, but only if he could quit after one year, in case it didn't work out so well.

James started his work by visiting all the best labs in Britain. He learned many tips on how to construct building that was good for lab work. For example, it would need a 50-foot tower with a huge water basin at the top, so that the water pressure could be used to run a strong vacuum pump.

James was required to give a lecture to celebrate the official opening of the lab, and in that lecture he stated his belief that science and math should be taught in various ways because people's brains have different learning styles. He said that scientific truths should be presented in various forms, so that everyone has a chance to learn. There should be not only books, but also colorful pictures and live demonstrations. Science should be for every type of learner, offering experiences in many formats: visual, verbal, and kinetic (doing).

The original Cavendish Laboratory building

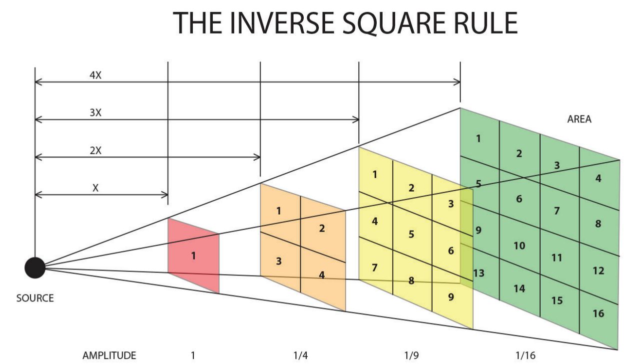
A funny incident occurred at about this time. Not everyone believed that experiments were important in education, and they doubted that Cavendish Lab would be successful. One staunchly anti-experiment professor told James that the only evidence a student needed was the word of his teacher. One day James happened to see this man walking past the lab, and he invited him to come in and see a demonstration of the conical refraction of light. The man replied, "No! I have been teaching it all my life and don't want my ideas upset by actually seeing it!"

Not too long after the lab had opened, James' friend, the Duke of Cavendish, (who had provided a lot of the money to build the lab), brought James a huge stack of papers. The Duke had found hundreds of pages of scientific notes that his uncle, Henry Cavendish, had written many years ago. These papers had only recently been discovered because Henry had never published them. The Duke's Uncle Henry had been a very strange person indeed. (Modern psychologist say that he probably had a very severe case of Aspberger's syndrome, a type of autism.) Henry disliked any and all interactions with other humans, especially women. He told his servants he never wanted to see them and that they should communicate with him by sliding written notes under his door. Only on rare occasions would he leave the house, and it was always to go to a scientific meeting. Publishing his papers would have required more contact with people, so Henry never did anything with the papers.

This is the only picture we have of Henry Cavendish. He refused to have his picture taken or his portrait painted. This sketch was done by an artist who remembered him.

Upon reading through some of these papers, the Duke realized that his uncle had made many key discoveries about electricity years before anyone else. If his uncle had published his papers, what we now called Ohm's Law would have been called Cavendish's Law. Henry discovered Coulomb's Law decades before Coulomb did. The Duke was looking for someone to read through all these papers and possibly get them published so that his uncle's work could get the credit it deserved. James was an expert in the science of electricity and he also knew how to write and publish, so he seemed the perfect person for this job. James had plenty of his own work to write about, but being a generous and kind person, he agreed to read Henry's papers.

James found that Henry had indeed been the first person to make many scientific discoveries. Henry had been much like James, being good at working with equipment, often finding clever ways of use simple things to test his ideas. For example, Henry thought that electricity followed the "inverse square law" first suggested by Isaac Newton to describe the gravitational attraction between stars and planets. The inverse square law says that when you move twice as far away, the strength of the force is cut by 2^2, or 4. If you move three times as far away, the force is reduced by 3^2, or 9. Four times as far would give you 4^2, or 16. Henry believed that electricity would follow this pattern. So he rigged up a shocking device, and gave himself electrical shocks of various current strengths and noticed how far up his arm the electricity traveled. James was intrigued by this experiment and decided to try it himself. He also tried it on many students and found that people who have tough, calloused hands have greater electrical resistance. A visiting scientist from America was appalled to find the famous James Clerk Maxwell playing with electricity and giving himself shocks!



James spent several years on the Cavendish manuscripts and this took time away from his own research. He could not have known that he had only a few more years to live. Had he known, would he have done anything differently? Perhaps not. James was not an egotistical person who believed that his own work was more important than anyone else's. He lived by the "Golden Rule" of doing to others as you would have them do to you. He didn't mind spending time publishing someone else's work, as long as it advanced the cause of science in general. Besides, the lab was named after Henry Cavendish, so perhaps there was some sense being obligated to this task.

James also got involved in writing and editing for the Encyclopedia Britannica, which had begun in 1768 and was then putting out its 9th edition. James wrote many articles for the encyclopedia and tried to make sure they would be understandable to the average reader. He also wrote articles for a new journal called "Nature," which would become one of the most prestigious science journals of the 20th century.

James was no longer young. He was in his 40s and students looked up to him as a fatherly figure. He had a passion for inspiring and encouraging his students. Though he could spot talented students and would make sure they were given the opportunities they needed, he didn't neglect his other students and believed that everyone had potential and had a role to play in the unfolding history of the world. He never spoke harshly or criticized anyone, though he would never back down from intellectual arguments when he believed he was right. Under Maxwell's leadership, Cavendish lab flourished. It quickly become an exciting place to work and began producing excellent experimental scientists.

James never gave up his love of funny poetry. Even in his last years, as director of Cavendish lab, he would still write funny poems about various events. When one of his young scientist friends, Henry Rowland, successfullly completed an experiment involving spinning a disc made of ebonite (a hard, black rubber) in a beam of light, James wrote:

The mounted disc of ebonite
Has whirled before, nor whirled in vain;
Rowland of Troy, that doughty knight,
Convection currents did obtain
In such a disc, of power to wheedle,
From its loved north, the subtle needle.

During the 1870s, many famous inventions were being developed. Alexander Graham Bell had just invented the telephone, and Thomas Edison was working on the phonograph. There were hundreds of other inventions that are now less famous than those of Bell and Edison, including a little curiosity called the radiometer. William Crookes, the inventor of the radiometer, could not even explain how it worked. It was a glass bulb containing something that looked like

Radiometers are a popular science toy even today.

James took a shot at explaining the mystery of the radiometer. He understood what sunlight was (waves of electromagnetic energy) and he had a lot of experience working with gases. There were still a few gas molecules left inside the radiometer, and those molecules would follow the laws of how gases behaved. He thought that the black side of the vanes was heating up because of the sun and this was causing the air molecules that were close by to speed up. These fast-moving molecules would then create a very small flow of air around and past the edges of the vanes. He called this the "slip current." Some of the molecules in this slip current would hit the edge of the vane as they passed, nudging the vane a bit in that direction. After thousands or millions of these nudges, the vane would begin moving around. He published a paper about this theory and even came up with some new equations about "rarefied" gases (when there are very few molecules present). This paper, along with all the interest in radiometers, created new branch of science, the study of rarefied gases. The place where this is most important is the study of the upper atmosphere.

The puzzle of the radiometer was not finally solved until the 1920s. It turned out that Maxwell was mostly wrong, although his idea of slip currents was basically valid. It was determined that it was the force of the heated air molecules hitting the black side of the vane that was driving it forward. James had made an error in his first equations and had simplified them too much.

While he was puzzling over the radiometer, James began having terrible heartburn. He found that baking soda helped to relieve the pain, but would not entirely cure whatever was going on in his stomach. He may have had what we now call a stomach ulcer, the root cause of which is often a bacterial infection. Left untreated, an infected ulcer can turn into a cancerous tumor, and this is what would happen to James. (Antibiotics would not be discovered for another 60 years, and the use of antibiotics to treat ulcers would not begin until another 60 years after that.) Katherine had also begun to have chronic health issues, and James was always more concerned about Katherine than he was about himself.

James spent the summer of 1879 at Glenlair, as usual, but did not have the strength to keep up with his normal routines. A friend would later say that "the spring had gone out of his step." In September of that year, one of James' colleagues from the lab came to see him at Glenlair. He knew that James was sick, but marveled at how well he still managed all his responsibilities. James gave his friend a tour of the estate, taking him to all the places he had enjoyed as a child, like the places in the creek where he had paddled around in the washtub. This was the last long walk that James would ever take.

By October James was in pain most of the time and the local doctor recommended that he go to Cambridge to receive treatment from a doctor who specialized in pain management. The Cambridge doctor was able to reduce his pain, but he could not stop the progression of the cancer. James died on November 5, 1879, at the age of 48. His mother had died of the same disease at about the same age.

The Cambridge doctor said this about James:

"The calmness of his mind was never once disturbed. His sufferings were of a kind that would try the patience of anyone, but they (the sufferings) were never spoken of by him in a complaining tone. In the midst of them his thoughts were rather for others than for himself. His only anxiety seemed to be about his wife whose health had for a few years been delicate and had recently become worse. While his bodily strength was ebbing away, his mind never wandered nor wavered. No man ever met death more consciously or more calmly."

James' local doctor, back at Glenlair, said this about him: *"I must say he is one of the best men I have ever met, and a greater merit than his scientific achievement is his being, so far as human judgment can discern, a perfect Christian gentleman."*

James rarely wrote about himself, but in those last years, he penned these words:

"What is done by what I call "myself" is, I feel, done by something greater than myself in me. The only desire which I can have is like David (king David in the Bible) *to serve my own generation by the will of God, and then fall asleep."*

Maxwell is buried in the cemetary behind Parton Kirk, near Glenlair.

The death of James Clerk Maxwell was a great sadness not only to his family and friends, but to the entire scientific community. If he had lived a few more decades, just think of how many more things he could have accomplished. He might have been the discoverer of the theory of relativity or the inventor of the light bulb.

There is a large bronze statue of James Clerk Maxwell in the city of Edinburgh. If you ask passersby who that statue represents, most of them don't have a clue. James seems to have been forgotten even by his own countrymen. But perhaps this is not too surprising, considering that James had lived a quiet life. He had never tried to promote his own work and he had stayed out of politics. He never sought fame or fortune. What he would like most about the bronze statue of himself is that it portrays him with his color wheel and with a dog, who we can be sure was named Toby.

James would be pleased to know that Cavendish Lab went on to become one of the best research facilities in the world. In the following century, the electron would be discovered there, as well as the structure of DNA. The lab has produced 29 Nobel Prize winners. He would also be pleased to see his famous equations printed in every college textbook on electricity and magnetism. At the time of his death, his theories and these equations had still not been accepted by everyone in the world of science. Even James' friend William Thomson doubted the equations. James was so far ahead of his time that it took several decades for everyone to really catch up to him.

Maxwell with his color wheel and Toby.

Maxwell's fame is much greater outside of Scotland. Other countries have issued commemorative postage stamps in his honor. This stamp shows Maxwell, on the right, with Heinrich Hertz, the German scientist who finally proved that Maxwell was correct about electromagnetic waves being more than just electricity or light. Hertz was able to generate what we now called radio waves. Scientists from all over the world have traveled to Scotland to see the places where James lived and worked. Right after the Berlin Wall came down in 1988, two bus loads of Russian scientists showed up at the church cemetery where James is buried. They said they had come to pay homage to Scotland's Einstein.

The current owner of Glenlair (as of 2017) is Duncan Ferguson. He was an only child, like James had been, and came to Glenlair as a young child, as James had. Duncan spent his late childhood roaming the woods and fields of Glenlair, just as James had. He feels a strong bond with James Clerk Maxwell, though he is not a blood relative. When asked what his overall thoughts are about James Clerk Maxwell, Duncan Ferguson says, "What appeals to me about Maxwell was how normal he was as a boy. He loved the open air and he loved all the creatures. All the gardens and trees you see on the property were planted by Maxwell. He loved it here, the same way I love it here. I've been offered lots of money for Glenlair, but there's no way they're getting me out of here."

James would be pleased.

Credit where credit is due: I could not have written this biography without having read Basil Mahon's biography called "The Man Who Changed Everything," published in 2003 by John Wily & Sons, ISBN 978-0-470-8617-4