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## A Light History of Electromagnetic Waves: Waves and Particles before Wave-Particle Duality

Brien Puff, 2009

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It is everywhere. In today's society, with today's infrastructure, one has to retreat far, far into the vast reaches of the countryside in order to lose most of it, and even then, one has to hope for the cloudiest night imaginable, one that even then lacks a storm and the inevitable flashes that go with it. It is so hard to hide from light, that when one finds oneself finally alone, devoid of it, awash in a sea of darkness, it is always a bit overwhelming, awing, and bewildering.

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Light was never really paid attention to until the time of the Enlightenment. The first major scientist to cover and hypothesize about light was Christiaan Huygens, a Dutchman. His book Treatise on Light from the late 1600's suggested that light was a wave, similar to that of a sound wave, or waves "formed in water when a stone is thrown into it, ...which present a successive spreading as circles, though these arise from another cause, and are only in a flat

surface."<sup>1</sup> Like those two examples, he said, light waves move "from the luminous body to our eyes by some movement impressed on the matter which is between the two." The matter that Huygens is referring to here, of course, is the æther, a scientific theory from the Enlightenment-era period. It is the invisible medium that scientists proposed filled the universe and through which the earth moves and so forth.<sup>2</sup>

About the same time that this was published, Isaac Newton, the famous Englishman, was working on his own book, which would become Opticks, to be published in 1704. In this groundbreaking work, Newton laid out the groundwork for what would become

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<sup>1</sup> Huygens, Christiaan, Treatise on Light, tr. Silvanus P. Thompson (Chicago: University of Chicago Press, 1912), <<http://www.gutenberg.org/etext/14725>> (accessed April 17, 2008).

<sup>2</sup> J.J. O'Connor and E.F. Robertson, "Isaac Newton," School of Mathematics and Statistics, University of St. Andrews, Scotland, <<http://www-history.mcs.st-andrews.ac.uk/Biographies/Newton.html>>.

the standard by which light was looked at for the next century and a half.

Newton, born 1653 to a family of common farmers, became interested in math, science, and astronomy after reading texts from Galileo and Kepler while he was at Trinity College Cambridge, and soon after produced his first book (Quaestiones Quaedam Philosophicae) addressing his own questions and thoughts on science. Even as what we would consider an undergraduate, Newton was already creating important works in the fields of math and science.<sup>3</sup>

While the plague was raging in England in the mid-1660's, Newton began work on what would become the basis of his great book on light. Among his lesser-known experiments were to poke his eye with a small knife to see how it would affect his sight and to look at the sun until he risked becoming blind.<sup>4</sup> More importantly (and more wisely), he began by using a prism to break up sunlight (which is, basically, just white light) into its component colors. This broke the theory that white light was just a single entity, that is, that it could not be broken down into any further elements. Even Aristotle had believed this, and most likely partly because of that, it had not been expressly questioned until Newton, and even then, it was an accident (he had noticed a chromatic aberration in a telescope that had resulted in him seeing the spectrum of colors; figuring this was a problem

with all telescopes with lenses, he invented his own reflecting telescope, known today as the Newtonian telescope).<sup>5</sup>

Because of his work with optics in this time, Newton was rewarded with a professorship at his alma mater, where the first course he taught was in that same subject. In 1672, he published his first paper exclusively on light in the Philosophical Transactions of the Royal Society, to which he belonged, that explained his thoughts on the components of light and other theories he had. This paper was controversial in the scientific community, raising concerns from men like Robert Hooke and even Huygens.<sup>6</sup>

Hooke took exception to many propositions that Newton made, and refuted them all in a letter to Newton and the Royal Society during the same year that the paper was published. From said letter, Hooke wrote,

But, tho' I wholly agree with him as to the truth of those he hath alledged, as having, by many hundreds of trials, found them so; yet as to his hypothesis of solving the phenomæna of colours thereby, I confess, I cannot see yet any undeniable argument to convince me of the certainty thereof. For all the experiments and observations I have hitherto made, nay, and even those very experiments, which he alledgeth, do seem to me to prove, that *white* is nothing but a pulse or motion,

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<sup>3</sup> Ibid.

<sup>4</sup> Rob Iliffé, "Newton's Optical Papers," The Newton Project, <<http://www.newtonproject.sussex.ac.uk/prism.php?id=47>>.

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<sup>5</sup> O'Connor and Robertson.

<sup>6</sup> Ibid.

propagated through an homogeneous, uniform and transparent medium: and that colour is nothing but the disturbance of that light, by the communication of that pulse to other transparent mediums, that is, by the refraction thereof: that *whiteness* and *blackness* are nothing but the plenty or scarcity of the undisturbed rays of light: and that the two colours (than the which there are not more uncompounded in nature) are nothing but the effects of a compounded pulse, or disturbed propagation of motion caused by refraction.<sup>7</sup>

What he is saying here is that, in opposition to Newton's theory that white light has different parts, different wavelengths, that all combine to make the total "whiteness," Hooke believes that the difference between that and the "blackness" of light is just a matter of intensity; the more light there is, the whiter it will appear, and the less there is, the blacker it will appear.

He also argued that color was no more than a perception in the human eye. When light is passed through a prism and refracted, he wrote, "a differing pulse is propagated" on all "parts of the ray," and when the differing pulses hit the eye, they are interpreted as the red, violet, blue, etc.

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<sup>7</sup> Robert Hooke, "Robert Hooke's Critique of Newton's Theory of Light and Colors (delivered 1672)," The Newton Project, <[http://www.newtonproject.sussex.ac.uk/texts/vi\\_ewtext.php?id=NATP00005&mode=normalized](http://www.newtonproject.sussex.ac.uk/texts/vi_ewtext.php?id=NATP00005&mode=normalized)>.

that Newton reported on as being different rays of light in themselves. Hooke compared it to sound (a comparison that was often made in the 17<sup>th</sup> and 18<sup>th</sup> centuries), and specifically, a noise coming from an instrument, "the ray is like the string, strained between the luminous object and the eye, and the stop or fingers is like the refracting surface, on the one side of which the string hath no motion, on the other a vibrating one." The different vibrations create different tones, which hit the ear and the brain perceives the difference between them as different sounds; this is exactly the principle that Hooke is trying to apply to the eye.<sup>8</sup>

Newton did not take kindly to this at all, especially since elsewhere in the letter, Hooke had accused Newton of stealing his ideas, and so began a feud that would last between them until Hooke's death in 1704 (it is no coincidence that Opticks was not published until this year; Newton held off on publishing it so Hooke would have no way to complain about it).<sup>9</sup> But, between 1672 and 1704, Newton had plenty of time with which to prove Hooke (who, as head of the Royal Society, became his main detractor and opposition) wrong and to prove his own thoughts and theses right.<sup>10</sup>

His seminal text Opticks was a summary of all the experiments and trials and hypotheses that he had had since

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<sup>8</sup> Ibid.

<sup>9</sup> Ralph Baierlein, Newton to Einstein: The Trail of Light (Cambridge: Cambridge University Press, 1992), 33.

<sup>10</sup> Rob Illife, "Newton's Optical Correspondence," The Newton Project, <<http://www.newtonproject.sussex.ac.uk/prism.php?id=111>>.

1672 on the field of optics. Of course, he had worked on other things as well in that time, most notably his Philosophiae Naturalis Principia Mathematica, but much of his time was devoted to optics. It has been said that though the Principia was more famous, Opticks was easier to read since it was printed in English, and thus it can be understood if the latter had a greater influence in general than former in the general understanding of science in the British Isles.<sup>11</sup>

The text itself was split up into books and what he called “Queries,” which were statements that basically summarized his experiments and the conclusions that he reached in his book. But what were they, or, what were the most important conclusions he reached?

Arguably the most important question he asked in his queries came in the form of Query 29: “Are not the Rays of Light very small Bodies emitted from shining substances?”<sup>12</sup> This one sentence has a much bigger impact than it suggests. First, and most shakingly, this suggests that light is an actual substance. It is implying that light has a mass, no matter how small it is, yet he says that they are weightless. And secondly, this is going directly against the wave theory that Huygens had proposed.

This became known as Newton’s corpuscular theory of light, taken from the fact that he, at one point, refers to the tiny bodies of light as “corpuscles.” And not only were they there, he argued, but there were corpuscles of different sizes that corresponded to the colors that those particular corpuscles

produced. Wrote Newton himself,

Nothing more is requisite for producing all the variety of Colours, and degrees of [refraction] than that the Rays of Light be Bodies of different Sizes, the least of which may take violet the weakest and darkest of the Colors, and be more easily diverted by refracting Surfaces from the [straight] Course; and the rest as they are bigger and bigger, may make the stronger and more lucid colours, blue, green, yellow, and red, and be more and more difficulty diverted.

This tells us that he considered the red light particles to be “larger” than those of the violet light, so therefore the red would be affected differently (specifically, less so) when a force is enacted upon the ray of light as a whole.<sup>13</sup>

The rest of the book was devoted to optical issues like refraction and reflection, two aspects of light that supported Newton’s corpuscular theory. The latter concept is simple to understand: the light just bounces off the surface that it comes incident to at the same angle at which it approached and angle normal to the point of incidence. On refraction, however, Newton projected something different than what the scientific community accepts today, mostly because his own theory was wrong in the first place: “Every Ray of Light in its passage through any refracting Surface is put into a certain

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<sup>11</sup> Baierlein 33-4.

<sup>12</sup> Ibid., 34.

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<sup>13</sup> Ibid., 40.

transient Constitution or State which in the progress of the Ray returns at equal Intervals, and disposes the Ray at every return to be easily transmitted through the next refracting Surface, and between the returns to be easily reflected by it.”<sup>14</sup>

Newton’s work was ultimately important because it provided one side of the wave-particle duality notion that we know of today. Since it would be wrong to paraphrase Albert Einstein in a formal paper and dilute the genius of his work, he wrote in his 1938 version of The Evolution of Physics that, “To keep the principal idea of Newton’s theory, we must assume that homogeneous light is composed of energy-grains and replace the old light corpuscles by light quanta, which we shall call *photons*, small portions of energy, traveling through empty space with the velocity of light. ...Newton’s theory in this new form leads to the *quantum theory of light*.”<sup>15</sup> This quantum theory of light (which really is just the corpuscular theory at its very base—that light is composed of small packets—but modernized) supports the wave-particle duality in that it says exactly that light will behave as a particle. The fact that modern physics (as well as Einstein himself) endorsed it did wonders to reestablish the acceptance of this particular theory.

Jumping back through time, however, Newton’s respected and somewhat exalted status in the scientific community of the 18<sup>th</sup> century meant that no one really appeared to doubt or challenge the results that he had come up

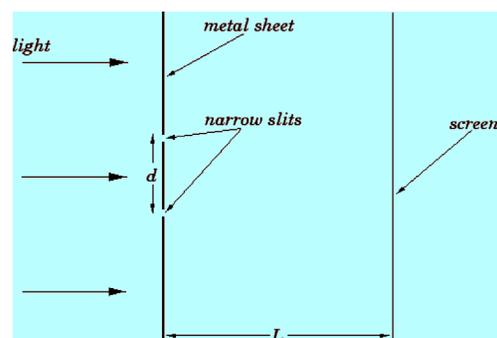
<sup>14</sup> Ibid., 41.

<sup>15</sup> Albert Einstein and Leopold Infeld, The Evolution of Physics (New York: Simon and Schuster, 1950), 275.

with. Newton was untouchable, especially now that Hooke, his prime opposition, was dead. But slowly, towards the 19<sup>th</sup> century, opposition began to rise up—to use a better term, not so much opposition to Newton, but more in support of Huygens and his wave theory of light.

In 1803, an English physicist who, of all people, had helped decode the Rosetta Stone four years earlier, came onto the scene. Though he was an admirer of Newton’s, Thomas Young had his own suspicions when it came to light that it was not actually (or not purely) a particle phenomenon, but it also had elements of Huygens’ wave theory. And, Young was able to prove that there is a definite wave property to light through his famous double-slit experiment.<sup>16</sup>

Young was inspired by his knowledge of sound as a wave, which



seems to pop up again and again in the 17<sup>th</sup> and 18<sup>th</sup> centuries, as mentioned before. He knew that if two equal but individual sound waves met, when the waves and their respective equations

<sup>16</sup> Richard Fitzpatrick, “Young’s Double-Slit Experiment,” Electromagnetism and Optics, an Introductory Course, University of Texas at Austin, <<http://farside.ph.utexas.edu/teaching/316/lecture/s/node151.html>>.

were 180 degrees out of phase, there would be no noise heard at that point (a phenomenon called phase cancellation). This can be likened to dropping two stones simultaneously into a still body of water; where the peak of wave one meets with the trough of wave two, they will cancel each other out, so it would be like there was no wave there. So, the interference causing the phase cancellation in that scenario would be the same as if light was a wave. If light had wave-like properties, then where the waves were 180 degrees out of phase, there would be no light.<sup>17</sup>

The figure above shows the set up for his experiment.<sup>18</sup> The light would enter from the right, split into two separate but equal waves through the narrow slits, travel through the distance  $L$ , and dark and light bands will appear on the screen exactly 180 degrees away from each other.

And, that is exactly what Young found. In 1807, he wrote,

The middle is always light, and the bright stripes on each side are at such distances, that the light coming to them from one of the apertures must have passed through a longer space than that which come from the other by an interval which is equal to the breadth of one, two, three, or more of the [wavelengths], while the intervening dark spaces

correspond to a difference of half a [wavelength], of one and a half, of two and a half, or more.<sup>19</sup>

So, what he said here is that there was both constructive and destructive interference on the screen when he passed the light through the slits, meaning that light did, in fact, have a wave-like property. This was a loud voice of support for the work of Huygens more than a century beforehand.

But, when Young presented his findings to the Royal Society, the same Royal Society that had been led by Newton's main opponent one hundred years earlier, he was derided for it. It was not accepted by the general scientific community until another physicist, this time a Frenchman by the name of Augustin Fresnel, came along twenty years and showed that light moves slower through a medium, whereas it was discovered that if Newton's corpuscular theory were true, then light would have to, in fact, propagate faster through media that were thicker or denser than air.<sup>20</sup>

That was not the biggest change in the history of the theory of light in the nineteenth century, however. Other scientists came and found various things about light, but nothing that was too ground breaking as compared to Huygens, Newton, and Young/Fresnel. Most work, in fact, between 1820 and the latter part of the century concerned the new interests in electricity and magnetism. Although, some work would

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<sup>17</sup> Or, in Young's words: "When two Undulations...coincide with either perfectly or very nearly in Direction, their joint effect is a Combination of the Motions belonging to each." Cited from *The Trail of Light*, page 94.

<sup>18</sup> Image retrieved from <http://farside.ph.utexas.edu/teaching/316/lectures/img1495.png>.

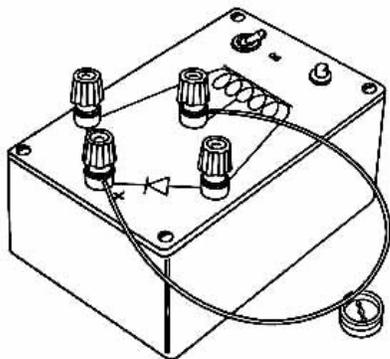
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<sup>19</sup> Baierlein, 95.

<sup>20</sup> Fitzpatrick.

actually contribute to advances in research involving light, and actually directly inspired the major figure in light in the late nineteenth century to make his particular findings.

In 1820, a physicist in Denmark named Hans Christian Ørsted was searching for a connection between



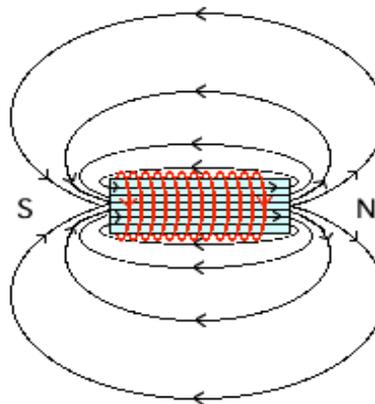
electricity and magnetism, thinking the two things to be related. It would turn out that he was right, and in an experiment he made during a lecture of his university physics class, proved that an electrical current can create a magnetic field by running an electric current through a copper wire set next to a compass (as seen in the diagram to the left); the needle of the compass was affected by the electrical current, and thus the conclusion was made.<sup>21</sup>

More than ten years later, back in London, former-bookbinder-turned-physicist Michael Faraday was working on just the opposite of that.<sup>22</sup> Seeing how Ørsted's electrical current could cause a magnetic field made Faraday

<sup>21</sup> Baierlein, 114-6. Image retrieved from <http://www.practicalphysics.org/imageLibrary/jpeg326/525.jpg>.

<sup>22</sup> Basil Mahon, The Man who Changed Everything: The Life of James Clerk Maxwell (Chicester: John Wiley & Sons, Ltd., 2003), 56-65.

wonder if the opposite was possible as well. The experiment he carried out was a relatively simple one involving only a magnet and a charged solenoid, a wire twisted into a tight tube (as seen in the diagram below)<sup>23</sup>. When Faraday inserted the magnet into the solenoid, an electric current was detected. When it was placed in the solenoid, however, the electrical flow stopped. Taken out again, the magnet caused the flow of electricity again. Thus, it was determined by Faraday that only a changing magnetic field (which emanated from the magnetic bar in loops called "lines of force" from the magnetic north pole of the magnet to the south and which has different values



at each point along each individual line of force) causes an electrical current.<sup>24</sup>

From this work that Faraday contributed to the study of electricity came the inspiration for James Clerk Maxwell, and for a little longer, a sidetrip down the road of research in electricity and magnetism is necessary to advance further towards wave-particle duality and the twentieth century in the history

<sup>23</sup> Image retrieved from <http://www.uvi.edu/Physics/SCI3xxWeb/Electrical/BfieldSolenoid.gif>.

<sup>24</sup> Baierlein, 116-8.

of light. Maxwell, the Edinburgh-born physicist, was searching for a unification theory, one that would tie together electricity and magnetism.<sup>25</sup> He had seen that the two were related from both the experiments by Ørsted and by Faraday, but he wanted to know if the two could be joined together.

In his search for 19<sup>th</sup>-century unification theory, Maxwell needed a good imagination and an even better ability to see hypothetical models in his head. He decided on using a model that consisted of tiny, spherical cells, thinking that the molecules in a medium were similar to that of these cells. What he wanted to do was to induce an electrical current through these cells, and he hypothesized that the magnetic field created by the electricity would cause these cells to spin, which would, in turn, cause adjacent cells to spin, and so forth, creating propagation through the field of the cells. The way the cells spun, too, he hypothesized, would dictate exactly what sort of magnetic alignment they would have. If a cell spun one way, it would be magnetically aligned with magnetic north; if it spun the opposite way, it would, of course, point towards the opposite pole.<sup>26</sup>

When he was actually doing the experiment, his predictions were correct. He also found that the cells themselves would store energy. Whenever he would turn off the electrical current that ran through the cell medium, the cells would continue to spin until the energy they contained ran out.<sup>27</sup>

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<sup>25</sup> Mahon 4.

<sup>26</sup> *Ibid.*, 95-102.

<sup>27</sup> *Ibid.*, 96.

He also found something amazing that would lead directly to the discovery he is most known for in today's world. Maxwell noticed that when an electrical current was induced into the cells, they would distort, meaning that particles moved in the cells towards one of the plates that was being used as a conductor of the electrical current. So, because these particles have moved, then that indicates that there is a charge on the plates now, one now with an excess of particles and the other with a lack of particles; by definition, as we know now, the latter would be positively charged and the former would be negatively charged. The cells would then be ready to spring back to what they had been before when the electromotive force becomes balanced again; said Maxwell, an "effect of electromotive force, namely, electric displacement, which according to our theory is a kind of elastic yielding to the action of force, similar to that which takes place in structures and machines owing to the want of perfect rigidity of the connexions [sic]."<sup>28</sup>

The speed of the movement was remarkably fast. In calculating the velocity of the cells, he found them to be moving at an in accurate rate, but close to 300,000,000 meters per second, or  $3 \times 10^8$  m/s (which is how measurements like this will be, when necessary, referred to from here on for the sake of ease).<sup>29</sup>

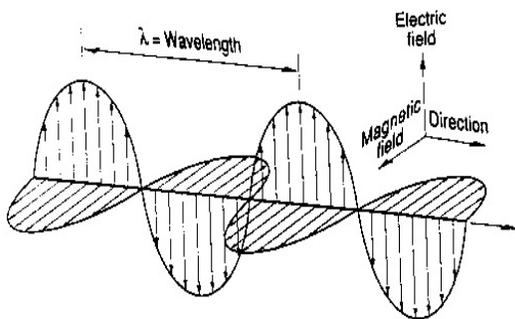
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<sup>28</sup> *Ibid.*, 105; James Clerk Maxwell, *A Dynamical Theory of the Electromagnetic Field* T.F. Torrance, ed., (Edinburgh: Scottish Academic Press, 1982), 38.

<sup>29</sup> Robert D. Purrington, *Physics in the Nineteenth Century* (New Brunswick: Rutgers University Press, 1997), 69; Mahon 122.

Maxwell suspected that this was close to the actual speed of light, which at the time was being actively measured by several different scientists in Europe. One German duo clocked the speed of light at  $3.1074 \times 10^8$  m/s. A French group found it to be about  $3.1485 \times 10^8$  m/s. So Maxwell knew that he was close, and he knew he had stumbled onto something big.<sup>30</sup>

There were three strong reasons that Maxwell first got the idea that electromagnetism and light were related like this. First, he knew that the electromagnetic waves were causing velocities of this speed because he “only made use of light...to see the instruments,” so there was no light involved in the experiment, so something else must have been moving so fast in the experiment.<sup>31</sup> Secondly, the way the particles were moving in the medium was



resulting in transverse waves, as opposed to longitudinal waves (also known as compression waves), which was the same type of wave that light was, which had been known previously and inferred from Young’s double-slit experiments.<sup>32</sup> And, finally, of course,

there was the speed of the movement. Nothing had ever really been timed as moving that fast before, so it could not have been much of a mere coincidence. The speed was too close to the recordings of the speed of light to not be significantly associated somehow.<sup>33</sup>

Maxwell had much to write about this. On the velocity issue, he wrote, “This velocity is so nearly that of light that it seems we have strong reason to conclude that light itself (including radiant heat and other radiations, if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.”<sup>34</sup> So even Maxwell had his questions with just one piece of evidence, but the other facts almost certainly cemented his suspicions. On the wave evidence, Maxwell wrote that the wave theory of light “requires us to admit this kind of elasticity in the luminiferous medium, in order to account for transverse vibrations...we need not then be surprised if the magneto-electric medium possesses the same property...we can scarcely avoid the inference that light consists in the transverse undulation of the same medium which is the cause of electric and magnetic phenomena.” And, ultimately, “The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field

<sup>30</sup> Ibid., 108.

<sup>31</sup> Baierlein, 122

<sup>32</sup> For clarity’s sake, transverse waves are what you might think of as waves in water, that is, physical movement that is perpendicular to the

direction of movement; longitudinal/compression waves are like sound waves or a Slinky, that is, physical movement along the direction of movement; Mahon 107.

<sup>33</sup> Baierlein, 122.

<sup>34</sup> Ibid.

according to electromagnetic laws.”<sup>35</sup> It is in this statement, this relatively simple statement, that Maxwell is saying that not only are electricity and magnetism the same thing, but that they are the elements of light. Light as an electromagnetic wave (see above picture for an example) was born.<sup>36</sup>

Maxwell published his findings at the end of his paper regarding Faraday’s work, “On the Lines of Force.” In 1865, however, he published them again as a paper unto themselves called “A Dynamical Theory of the Electromagnetic Field.” In this paper, Maxwell reports all of his findings on electricity and magnetism from this experiment, along with further revelations that moving electromagnetic waves have a moving electromagnetic field and included in Part III of the paper what became known as Maxwell’s Equations: equations of electrical displacements, magnetic force, electric current, electromotive force, electric elasticity, electric resistance, free electricity, and of continuity. These were read to the Royal Society before they were published in December 1864.<sup>37</sup>

The reaction was favorable. In the span of several years after that, he left his position in London and was hesitant to accept the position of head chair of experimental physics at the University of Cambridge. He taught, did his research, and edited the works of Henry Cavendish, a former professor at

the university. He did, however, get complaints and disagreements from other scientists on his views on the theory of æther, which he supports. The most notable opposition he saw from this was from William Thomson, who said that he “can not see” where he could prove this “inconceivable” and “misty” æther.<sup>38</sup>

Maxwell responded to this thinking he was correct, but as we know today, he was not: “I have now got materials for calculating the velocity of transmission of a magnetic disturbance through air founded on experimental evidence without any hypothesis about the structure of the medium or any mechanical explanation of electricity or magnetism.”<sup>39</sup> Aside from that, though, there was nothing wrong with Maxwell’s electromagnetic theory of light.

And, Maxwell’s theory helped lead directly to the discovery of the photon and the photoelectric effect, and ultimately the concept of wave-particle duality, wherein light exhibits qualities of both waves and particles; the wave portion of the theory is supported by the work of Maxwell, Huygens, and Young, whereas the particle theory (the correct portions of it) is supported by the work of Newton and later on in the twentieth century by Einstein. Einstein actually used the basis of the photon (now that it was discovered) to help win his Nobel Prize for Physics in 1905.<sup>40</sup>

Ultimately, the idea of light evolved much the way Darwin’s theory

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<sup>35</sup> Maxwell, 86.

<sup>36</sup> Purrington, 68-9; image retrieved from [http://www.mtholyoke.edu/~mlyount/MySites/Pictures/e\\_mag.JPG](http://www.mtholyoke.edu/~mlyount/MySites/Pictures/e_mag.JPG).

<sup>37</sup> Purrington, 69.

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<sup>38</sup> Ibid., 70; P.M. Harman, *The Natural Philosophy of James Clerk Maxwell* (Cambridge: Cambridge University Press, 1998), 113.

<sup>39</sup> Ibid., 113.

<sup>40</sup> Baierlein, 156.