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2/16/18

Background research summary becoming paper draft

I’ve added detail to what I already had from papers I had already read, and am also adding an overall narrative to the paper. For that, I’m thinking about the usefulness of this historical research in teaching Maxwell’s equations. To that end I’ve added some information from a paper I read on why physicists should study history and my thoughts on how this historical background is useful in understanding Maxwell’s equations better. There’s a lot of editing that remains for me to do on what I’ve added. I also want to eventually add some of the actual equations that different people used and describe the transitions between them, but I will focus on writing more for now, and adding equations next week.

**Early Electromagnetism**

In the early days of electromagnetism, many scientists were working on varied and still disjointed topics, including Oersted, Ampere, Biot, Savart, and Faraday (Arthur, 2013). For example, Gauss thought that electric actions propagate with finite velocity, but did not publish this work, because he couldn’t prove it (Sengupta & Sarkar, 2003). Oersted discovered that a steady electric current will create a magnetic force, and Ampere described this in equation form (Israelson, 2014). Faraday’s work includes discovering (or continuing work on) rotational magnetic field around electric current, induction, diamagnetism, dielectrics, and more (Israelson, 2014). Maxwell brought together much of this work.

Faraday proposed that magnetic lines of force (sometimes also called lines of flux) extended everywhere in space (Israelson, 2014). It’s interesting to note the differences between how Faraday thought about these lines compared to how we think of field now. He thought there were many particles in the medium between charges that all exerted forces, thus not fixing “action-at-a-distance,” but limiting the distance to be very small. Faraday’s theory was “the first precise and quantitative concept of a field” (Israelson, 2014, p. 8), and he did not live to see his theory accepted. When Faraday was about 65, Maxwell was about 25 and well positioned to pick up Faraday’s work. Faraday had little formal education and liked to keep physics conceptual rather than mathematical. He thought of his “magnetic lines of force” as being things that physically exist, because they were capable of explaining experimental results. Maxwell had more formal math training and did so much more than just write 20 equations describing Faraday’s field. Israelson says (2014, p. 11), “Maxwell defined a new kind of theoretical physics in which the classification of mathematical quantities, vector symbolism, and Lagrangian dynamics became major construction tools.” Thus, through the production of a specific piece of physics, Maxwell changed all of physics.

**Maxwell**

Most authors characterize Maxwell as picking up from Faraday’s work specifically (Israelson, 2014; Sengupta & Sarkar, 2003; Bork, 1963; Arthur, 2013). Many also agree though that Maxwell synthesized all prior work done by the lengthy list of scientists above (Sengupta & Sarkar, 2003; Arthur, 2013), but more research needs to be done on the ways Maxwell interacted with work by earlier scientists like Gauss, Ampere, etc. Few papers describe this explicitly. Perhaps, this is because there is no record of the explicit references, and Maxwell was instead influenced by these scientists’ work indirectly and did not reference them. There is one implied link in the literature from Gauss’s work to Maxwell’s, though. Riemann was a student of Gauss’s who continued trying after Gauss’s death to prove Gauss’s idea that electric actions propagate with finite velocity (Sengupta & Sarkar, 2003). Maxwell wrote a paper comparing his work to his contemporaries, like Riemann, Weber, and Lorenz (Bork, 1963), so it’s likely he knew of Gauss’s work through Riemann. Clearly, he was influenced in direct and indirect ways.

The first of Maxwell’s three major papers is based directly on Faraday’s idea of magnetic force lines (Bork, 1963). In his second and third (refined from the second) paper, he writes 20 equations describing the electromagnetic field, first termed in his third paper (Bork, 1963; Israelson, 2014). According to Israelson (2014, p. 9), “The specific concepts that Maxwell adopted from Faraday included the field-based definitions of electric charge and current, the concept of conduction as the competition between polarization build-up and decay, and the reduction of all electric and magnetic actions to stresses in the field.” In the earliest forms of Maxwell’s equations, he thought about electromagnetic actions in a mechanical analogy through the concept of “molecular vortices,” but he ultimately switched from this theory to Faraday’s theory of field (Arthur, 2013, p. 62). Maxwell’s idea of field was that it pervades all of space and physical media alike, avoiding the problems of action-at-a-distance, although he seems to have thought about the field as being in the ether. Thus, he modified Faraday’s idea of a field, bringing it slightly closer to the modern idea.

The main concept he adds to the work of those before him, besides furthering Faraday’s field theory, is the idea of displacement current. Interestingly, he never makes the explicit argument of the symmetry of equations when including displacement current, despite this being a common modern one (Bork, 1963). Such an argument only comes later in the work of those who refined Maxwell’s equations.

**Electromagnetism after Maxwell**

Maxwell’s contemporaries, Boltzmann, Hertz, Kirchoff, Lorenz, and Weber did some work that helped cement Maxwell’s equations (Arthur, 2013). For example, Hertz’s discovery of electromagnetic waves helped Maxwell’s theory gain traction in the scientific world, as it had suggested the existence of electromagnetic waves (Sengupta & Sarkar, 2003). Maxwell’s work was poorly received at first, but picked up traction.

Oliver Heaviside was a major player in bringing about the final form of Maxwell’s equations. He was first to explicitly discuss the symmetry of the equations. In his *Electromagnetic Theory*, he “modifies and extends Maxwell’s equations” (Bork, 1963, p. 5) building on it with rationalized units, vector notation, and symmetry. Heaviside was among several to condense and clarify Maxwell’s equations (Arthur, 2013), some of whom are called the Maxwellians (Sengupta & Sarkar, 2003). Heaviside converted Maxwell’s wieldy quaternions to vector algebra notation, writing div and curl, while Gibbs introduced notation similar to modern notation. Heaviside did not condense the 20 equations but his equations did include four that look similar to the four Maxwell’s equations recognized now. Hertz further clarified the equations (sometimes known as Maxwell-Hertz equations), mostly by removing the potentials and giving them separate forms for free space, conductors, and more (Arthur, 2013).

**Modern Electromagnetism**

This brings us to the generally accepted way of writing Maxwell’s equations and explains how Maxwell came to be a pivotal person in the formulation of electromagnetism by synthesizing the work done before him and influencing the work that followed. However, the equations have not remained static, untouched entities since the time of the Maxwellians. There is still a variety of way to express, conceptualize, and prove Maxwell’s equations. An example of one of the many modern ways of thinking about Maxwell’s equations is Feynman’s proof, using only Newton’s laws of motion and commutation relation for position and velocity of a nonrelativistic particle (Dyson, 1990). Feynman hoped from this proof to find physics models that were not describable through Lagrangians or Hamiltonians (Dyson, 1990, p. 2). Since it did not do this, Feynman considered the proof a failure, but Dyson considers the proof a successful historical relic to give context to historical physics.

A more typical modern version of Maxwell’s equations is the tensor form used to express the equations in consistent relativistic language (Griffiths, 2017), credited to Minkowski (Arthur, 2013). The current relativistic form came into being partly due to various thought experiments about relativistic electromagnetism. One such thought experiment shows that the classical forms of the electromagnetic equations yield a dipole moving with constant proper acceleration and no external force – self-sustaining motion (Cornish, 1986). The energy for this motion comes from the electromagnetic field (Griffiths, 2017). This seems to suggest the intermixing of the electric and magnetic fields in different frames in relativity.

**Discussion**

This historical background of Maxwell’s equations makes many things clear – some physics content and some tangential but important descriptors of the nature of science – some of which I already knew and now understand more deeply and some of which I did not know beforehand. The biggest truth that this history has pointed out is that science is not something done by any one person. This is certainly something I already knew but it has been eye opening to realize how scientists draw on other scientists’ work without even always knowing and certainly without always directly referencing it. This is not a good scientific practice (to miss referencing those whose work contributed to yours), but to a certain extent seems to have been unavoidable at times in history. It’s annoyingly difficult to find information on exactly how Maxwell was influenced by other scientists than Faraday, just that he was. There doesn’t seem to be documentation of how Gauss’s ideas reached Maxwell. Similarly, Lorentz presented a small set of electromagnetic equations for a microscopic model, never referencing Maxwell (Arthur, 2013). To some extent, it seems there is societal knowledge passed around in unclear ways, something of which we should certainly be wary.

This brings me to the next thing made clear from doing this research. It’s difficult to find a clear linear, chronological history of Maxwell’s equations, and especially difficult to find one source that details the whole process, just bits and pieces in different papers. This suggests many things: (a) the whole narrative is too lengthy and involved for the length of one paper (b) it’s difficult to describe a clear linear historical story as history is messy and nonlinear, and (c) there is a lot of remaining work to be done in telling the history of physics. I didn’t expect it to be so hard to find descriptions of the different forms of equations throughout history and how they changed as different scientists worked on them. This points to my flawed conceptual model of how equations come to be, expecting more linear passing on than actually happens.

I also find it interesting that it seemed that Maxwell was the center point of a great scientific movement that narrowed into his work and then broadened back out again. There was so much work prior to Maxwell that Maxwell synthesized that then also led to such a wide range of new physics. An open question remains if some scientists really do stand out as pivot points in history or if it only seems this way because, for example, we call the pivotal electromagnetic equations “Maxwell’s equations” rather than “Gauss-Faraday-Maxwell-Heaviside-Hertz-etc. equations.”

This historical research has also taught me how much physics is done in collaboration, how changeable it is in time, that sometimes people try something that’s not necessarily wrong but doesn’t add anything new to physics, etc. These all seem like they could be useful things for students to learn firsthand through learning more history in physics. I expected going into this paper to better understand Maxwell’s equations from learning their history, which is only partly true, but there are many other things that history can teach.

**Implications for Teaching**

Stanley (2016) argues that more history should be taught in physics for many reasons, some of which align with things I have learned from this research. He suggests that physics teaching often neglects to teach things like the messy, social aspect of physics, and that learning the history of science can help fill this hole. The history of physics shows that physics is social and needs many kinds of people, showing a more human side of physics that may help physics student retention. Learning history can also point to new science questions and foster curiosity, showing that physics isn’t finished. Some of this is what I learned in my historical analysis, suggesting some usefulness to teaching Maxwell’s equations with a bit more history.

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