# On primary sources in physics

A student wanted to interview me about the role of documents in physics, probably because of some gen-ed course; here was what I told him:

> *On 4/10/2016 12:08 PM, ¡a student¿ wrote:*
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> *Prof. Freeman,*
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> *Here are the questions that I set up for the interview. The theme revolves around the importance of historical documents in my respective field (In this case, through the Science/Engineering branch) and the impact they've had on what research is done today and the improvements that have also been made due to these documents.*
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> *- What important works of research (such as theories and treatises) from the past are considered most critical for a field of science such as physics and/or engineering?*

This is an interesting question, because (in physics, at least), the actual works aren't the important part. When we study physics, we aren't all that interested in studying the works of past scientists, because – unlike in many fields – our primary sources aren't the writings of the past. There is only one primary source in physics, and it is the structure of the universe that surrounds us. We have a mentality that no single document is authoritative, since built into the fabric of science is a mistrust for authority, of sorts: the only authority is Nature itself. When a physics student studies physics, she learns to construct, from the ground up, the entire edifice of knowledge about the universe, relying only when necessary on narratives involving famous experiments that are beyond her resources to replicate.

So, why do we read the great physics papers of the past? Well, in part, because we are interested in the things that our predecessors thought and found out. However, those things have been chewed up and reformulated over the years by so many of us; many of us have not read the writings of Newton, either in Latin or English. But people learned from Newton, and wrote and taught them, and over the years they have been reimagined and simplified and expounded upon; these days, the primary source for most of us concerning Newton's field of study is a humble book called simply Classical Mechanics, by a fellow named Goldstein. I'm sure in a few decades his book will have passed into history, and students will learn from something else, because the exact source isn't important. What's important are the truths about the way the world works. While in some fields the need to preserve primary sources is paramount, and the concern for exactly what words Shakespeare wrote makes sense, in physics Nature is our primary source, and She hasn't changed since the beginning. I know, for instance, that Gauss, Faraday, Maxwell, and Ampere discovered the properties of electromagnetism. However, I can't even name any of their original papers, because their titles, and the words in them, are not important. What is important are their ideas:

- Electric charges produce electric fields radiating away from them
- Electric currents produce magnetic fields circulating around them
- Changing electric fields produce magnetic fields circulating backwards around the direction of change
- Changing magnetic fields produce electric fields circulating around the direction of change

These ideas aren't written in Maxwell's original language, nor are they written in the language that you'll find them written in within a textbook. Rather, they're how I understand them; each physicist will understand them in a different way. These ideas, rather than the exact documents left behind by Maxwell, are what's important.

We also read them, however, for another reason. Physics is all about modes of thought, and we read the writings of our ancestors to understand how they thought – not what they thought as much as how. In the 1960's there were a great many papers concerning the structure of the particles we now understand are made up of quarks. Many of the ideas in them aren't even correct, but the crucial element is the growing awareness of the centrality of symmetry to the structure of matter.

Likewise, the ideas mentioned above – the keys to classical electrodynamics – have some interesting stories behind them, and these stories are what we glean from the documents:

- Faraday was bad at mathematics, and envisioned everything as the geometric interaction of electric and magnetic fields; we owe the "field" picture to him, and the centrality of vector analysis to so much of physics
- Maxwell simply guessed a new law of physics, and saw that it predicted traveling electromagnetic disturbances moving at around 300 million meters per second; the speed of light was previously measured as this value, so he indirectly discovered the nature of light

Nonetheless, I can name a few crucial moments in physics history – not the documents themselves, generally, but the ideas, since they are what's important:

- Galileo was one of the first to try to analyze motion mathematically and rigorously, and people usually call him the first physicist
  - This idea that we can use math is absolutely crucial for all of modern physics; the understanding that mathematics isn't just an exercise in logic but can actually rigorously tell us how the world works is essential for all modern science and engineering.
- Newton understood that all motion works in the same way, and wrote down the law of gravity, in his book Philosophiae Naturalis Principia Mathematica; he was the first to understand the importance of thinking about infinitesimally small changes in things, which is the discipline of calculus;
  - Newton's laws of motion are the basics of any science that studies the motions of things – which, as you might expect, is everything. The idea of thinking about infinitesimal changes in things (calculus) is even more fundamental, since it gives us the power to ask questions about rates of change, and thus to understand in a very general way how different quantities relate to one another.
- Gauss (and some of his contemporaries) developed the discipline of differential equations, and increasingly realized that these were the simplest forms in which to write down natural laws;
  - This is an extension of Newton's work on calculus, but Gauss' mathematical genius really deserves its own category; he made so much progress in actually solving the resulting equations that without his work on mathematics, a hundred years before computers, we wouldn't understand the consequences of the laws of physics
- Boltzmann applied the principles of statistics to the collective behavior of a great many particles, giving us a tool to understand temperature;
  - Statistical mechanics is crucial for the study of temperature, of phase changes from solid to liquid to gas, the behavior of magnetic materials, and many other things. More recently, the idea of "entropy" has been understood as a proxy for information, and in one of the odder stories in physics, actually is used to calculate things related to the flow of information in cellphone signals!
- Faraday and Maxwell (among a few others) gave us the complete picture of electromagnetism, the idea of the "field", and explained what light was;
  - This is absolutely crucial for electronics and electrical engineering, but the picture of "field" that Faraday relied on is the predecessor of modern quantum field theory, which is the closest we have to a "fundamental explanation of everything".
- Einstein (among some other things) understood that space and time are really two forms of the same thing, and unified the "position dependence" and "time dependence" parts of the laws of nature; he also understood gravity as a curvature of space
  - Relativity is an enormous revolution, since it means that fundamentally any law of physics must discuss "space" and "time" in the same way.
- Schroedinger, Heisenberg, and their collaborators discovered quantum mechanics, which describes the behavior of everything the size of an atom and smaller, and thus explained the periodic table;

- Quantum mechanics is the basis of all modern chemistry and materials engineering, and began the "particle physics" revolution: the idea that nature has small pieces out of which everything is made is as old as the Greeks. But this isn't helpful unless we can understand from the bottom up how those small pieces work; QM lets us do that.

... and some more recent discoveries which I shall omit. *(NB: Reading this a second time perhaps I should have mentioned Noether's theorem, but it is perhaps too mathematical for a piece written for an introductory student who is not a physicist.)*

My field of study is computational quantum chromodynamics, so out of these, I rely on the idea that nature can be described by fields (Faraday), interacting according to the rules of quantum mechanics, whose fundamental behavior is described by a differential equation (Gauss), on a stage where space and time play equal roles (Einstein). We use ideas borrowed directly from statistical mechanics (Boltzmann) to use randomness to conduct computer simulations.

> - *Where do you see the trajectory of your field going? Are there any important patterns, or trends you can observe from past advances that have helped make what is researched today more timely?*

It's hard to predict. I think, however, that physics is diverging; like a star that has gone red giant, casting off its outer layers and leaving only a core behind, the successes of physics in explaining so many of the phenomena around us have led to an explosion of applied physics, disciplines that make use of the findings of fundamental physics to build things. Physical chemistry is applied quantum mechanics; biophysics is the principles of physics applied to living things; and so on. Physics has now answered all of the fundamental questions about how Nature works down to sizes smaller than an atom, so the work in fundamental physics is now increasingly far removed from technology: the discovery of the Higgs boson, gravitational waves, and the like are aesthetically fascinating and philosophically rewarding, since they amount to, in Einstein's famous words, "knowing the mind of God".[1] However, they don't help us cure cancer, build better computers, or power the world's lightbulbs. That is the domain of applied physics, and I foresee that applied physics will become increasingly predominant. In 1890 Maxwell's discovery that light was an electromagnetic wave had immediate applications in radio, etc., but the same will not be true today; nobody is going to order pizza by gravitational wave signals.

However, the patterns of thought, the mental discipline involved in physics, are the same between pure and applied physics. We think about the world in the same way, ask questions in the same ways, solve problems in the same ways, and have the same belief in fundamental natural laws with universal application. And that brings me to the one primary document I will mention: The Feynman Lectures on Physics. Richard Feynman was a great physicist, great teacher of physics, and great philosopher of science; he gave a series of lectures covering the wide sweep of physical knowledge intended for beginning students that were collected in three volumes. (I am actually using one as a mousepad now!) They are remarkable not just for the knowledge they contain about how the world works, because as I mentioned the only primary source for the laws of Nature is Nature herself; rather, Feynman had a rare talent for solving problems, and a way to look at any problem and describe it in a simpler, more accessible, and yet sometimes more philosophically profound way than anyone else. These books are used by PhD students around the country to study for their qualifying exams, not because they contain any new information, but because they show the particular way that one of our discipline's greatest minds thought about the world around him.

Feynman died with the phrase "What I cannot create, I do not understand" written on his blackboard, along with "Know how to solve every problem that has ever been solved." This is the legacy of physics: we are a discipline continually rediscovering itself from the ground up, churning through our old documents and writing new ones, and studying most directly the patterns in which our predecessors thought; we can, of course, always look at Nature herself to rediscover the conclusions their thoughts led them to.

[1] Einstein, like many physicists, sometimes used "God" as a wry metaphor for "Nature and all Her works".