Studying Early Stage Science

Research Program Introduction

Version 1.9

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Leverage Research

1. Introduction

Scientific progress is responsible for some of the most amazing developments in human history. It has enabled us to cure diseases, increase agricultural yields, and travel quickly and safely across the globe. As such, the opportunity to enable progress in science can be very valuable.

Having studied examples from the history of science, we believe it is possible to describe how early discoveries led to the creation of impressive and sophisticated scientific disciplines. By understanding the methodologies used by the researchers at key points in the past, as well as the social and institutional contexts that enabled them to make progress, we believe it may be possible to help modern researchers make progress in new or stagnating fields.

In this paper, we outline a research program designed to investigate this hypothesis. We describe three important examples from the history of science, identify a phenomenon worth studying, state a specific formulation of our hypothesis, and describe our research methodology.[1] With this paper and the work that follows it, we hope to set the stage for the study of early stage science.

2. Three Historical Cases

2.1. Galvani, Volta, and the Invention of the Battery

In 1780, an Italian physician and biologist named Luigi Galvani announced the discovery of a new electrical phenomenon, which he called "animal electricity."

For some time, Galvani had been performing experiments using dissected frogs to investigate how electricity interacted with animal bodies. In his most famous experiment, he found that he could make dissected frog legs twitch by hanging them on iron hooks and

[1] A later paper will situate our investigation in the surrounding literature, including describing our relation to Kuhn, Popper, Lakatos, historicism, methodologism, natural epistemology, and complementary science.

probing them with a piece of metal. He concluded on the basis of his investigations that an electrical charge was being generated by the frog leg itself, and that this “animal electricity” was generated by an electrical fluid in the frogs (Cajavilca, Varon, and Sternbach 2009, 160).

Figure 1: Galvani experimenting on frogs

Galvani’s research attracted others to investigate animal electricity. In particular, it drew the attention of an Italian physicist and chemist by the name of Alessandro Volta.

Volta began to suspect that electricity was being generated from a source other than the frog itself. Volta’s hypothesis was that the electrical charge was instead created by Galvani’s use of different metals to mount and probe the frog leg, and further that certain metals were naturally disposed to pass an electric charge given the presence of a conductor.

To test his hypothesis, Volta needed some way to detect the presence of an electric charge. In the days before the invention of precise instruments for measuring electricity, this was no small challenge. Others had used the creation of visible sparks or the physical sensation of getting an electric shock as a way of detecting electricity, but these effects tended to require a strong current and Volta suspected that the current involved in the frog leg experiment was relatively small.

He needed a more sensitive instrument. So, he used his tongue.

He reasoned that if a frog leg would conduct electricity, his tongue probably would too. And, Volta knew from previous experiments that an electric charge applied to the tongue could create a bitter sensation. This let him conduct an experiment: he touched either side of his tongue with combinations of metals and used the presence or absence of the bitter sensation to detect an electrical charge. He found that some combinations of metals did cause the bitter sensation, leading him to conclude that it was in fact the metals that passed a current through his tongue, rather than his tongue generating its own "animal electricity" (Cajavilca, Varon, and Sternbach 2009, 162; Shock and Awe: The Story of Electricity 2011).

Subsequent investigations led Volta to make further breakthroughs in understanding the ability of metals to transmit an electric charge. He eventually discovered that he could generate a strong and consistent electrical charge by stacking zinc and copper on top of one another in an alternating pattern with brine-soaked cloth or cardboard in between.

Volta's invention was dubbed the Voltaic pile, and was the precursor to the modern battery.

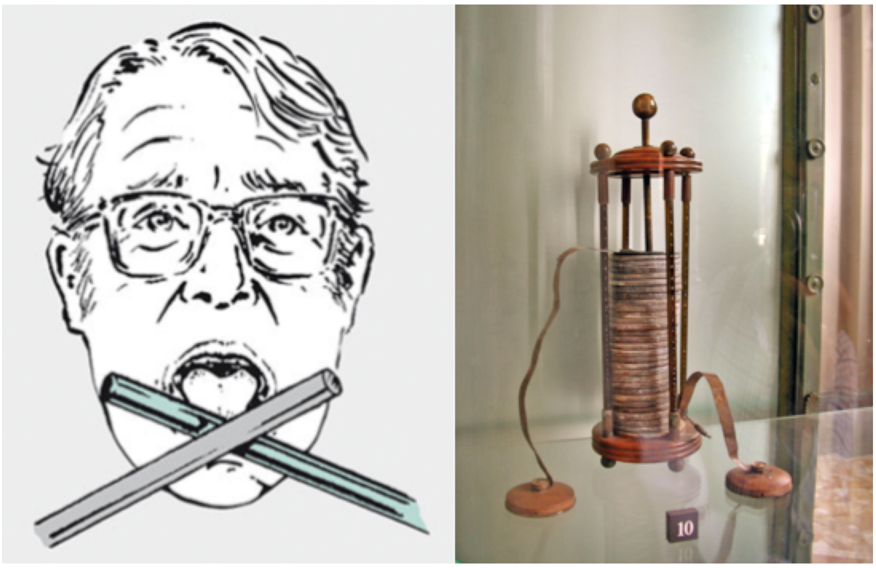

Figure 2: Volta's experiment and the Voltaic Pile

The debate between Galvani and Volta over animal electricity and related topics would result not only in the Voltaic pile, but also in the early development of the fields of electrophysiology, electromagnetism, and electrochemistry (Cajavilca, Varon, and Sternbach 2009, 159).

While the two had deep theoretical disagreements, Galvani's creative experiments identified a phenomenon — frogs twitching when touching two pieces of metal — which Volta was able to study with a unique method of his own, using his tongue instead of a frog. Galvani's theory of animal electricity was wrong, but his work enabled further research that led to the creation of the voltaic pile and the foundations of our modern understanding of electricity.

Volta and Galvani both had to develop many of their own theories in the absence of an accepted paradigm for electricity, and both had to design their own experimental tools and methods. The trajectory of their respective research programs, and of their research efforts combined, would have been hard to predict in advance. They tried anyway, and their work helped turn the study of electrical phenomenon into a fully developed scientific discipline.

2.2. Galileo and the Development of Telescopic Astronomy

The history of science includes a number of cases of scientific progress that share some of the notable features of Galvani and Volta's research. Another example is the story of Galileo and the early development of telescopic astronomy.

Galileo Galilei pioneered the use of the telescope to observe celestial objects. He observed Jupiter's moons, the phases of Venus, Saturn, the existence of sunspots and more. Initially though, Galileo had trouble convincing others of the reliability and usefulness of the telescope. When Galileo visited Bologna in 1610 to demonstrate his telescope:

> In the presence of a number of learned men, Galileo showed his telescope and let others observe earthly and celestial things through it. They agreed that for earthly objects the instruments performed as promised but that in the heavens it was not reliable. Although Galileo's notes show that on the first night two and on the second night all four of the satellites were visible, none of the gentlemen present were able to see satellites around Jupiter. (Van Helden 1994, 11)

The learned men were skeptical of Galileo's device for understandable reasons. The optical principles behind the device were not well understood at the time and some of Galileo's claims about the heavens contravened established wisdom on the topic. Furthermore, Galileo's telescope was not a very powerful or easy-to-use instrument. His telescope was capable of no more than 20x magnification and a field of view of around 15 feet, whereas one can purchase a modern amateur telescope today for around 100 USD that is capable of 10 times greater magnification (200x) and a field of view 34 times larger (516 feet) (Sky and Telescope 2017; Telescopic Watch 2019).

To illustrate the difficulties this posed, compare the image of Ely Cathedral viewed with a modern telescope at the same zoom as Galileo's telescope (20x) with the field of view available to modern telescopes (Figure 3, top picture), with the image of the same object at the same distance with a replica of one of Galileo's telescopes (Figure 3, bottom picture).

Figure 3: Top picture - modern telescope at 20x zoom; Bottom picture - replica of Galileo's telescope, also at 20x zoom (Astronomy and Nature TV 2010)

The small circle in the middle of the bottom picture is the field of view available through the replica telescope. The light colored area shows the visible portion of the cathedral.

In addition to the small field of view, Galileo lacked modern equipment for mounting and stabilizing his telescope. This meant that even if Galileo could find the relevant astronomical object in the small field of view, ensuring that the telescope remained fixed on that object for repeated observations was a significant challenge.

Finally, even under optimal circumstances, it is not uncommon for a user of Galileo's telescope to fail to see what they are meant to see. The instrument takes a certain amount of getting used to as the eye and brain become accustomed to interpreting the image and not everyone has sufficiently good eyesight to use the device properly (Van Helden 1994, 11). As one historian of science notes:

> On several occasions I have taken a group of my students to look for Jupiter's satellites through a replica of one of Galileo's telescopes – students who were convinced the moons were really there –

> and the results were always mixed. Some saw all that were visible, some saw one or two, and some saw none at all. No matter how public the occasion, the actual observing remains an individual and private act. (Van Helden 1994, 12)

Indeed, the private nature of telescopic observations created difficulties in settling scientific disputes. For example, in 1643, Antonius Rheita published a book announcing the discovery of new satellites around Jupiter and Saturn. While others reported not seeing the satellites, Rheita claimed the satellites could only be seen with the new, more powerful telescope he had invented. All telescopes at the time were hand-made and thus differed in clarity and magnification, and so scientists could not simply use their own instruments to confirm or disconfirm each others' claims as their failure to replicate results could be the consequence of inferior equipment. Scientists eventually reached agreement on this question in 1647, when Hevelius (who claimed to have built a still more powerful telescope), was able to convince scientists that the supposed satellites were actually fixed stars behind the planets (Van Helden 1994, 8-20).

The telescope was initially an unreliable, poorly understood tool. It did not produce directly shareable or replicable results and in practice often created scientific disputes that were difficult to resolve. Yet despite the challenges it posed, the telescope did sometimes allow early telescopic astronomers to make observations that were more detailed than those available to the naked eye. This modest improvement was enough to attract a small number of early scientists who began working with the device. Over time, they learned more about the optical principles involved, improved at grinding lenses for new telescopes, and developed more effective ways of communicating their findings to other astronomers and the public.

2.3. Black, Lavoisier, and the Chemical Revolution

In 1756, Joseph Black published his *Experiments Upon Magnesia Alba* in which he described experiments he performed on an unusual substance which he called "fixed air." Black originally discovered the substance[2] through experiments on magnesia alba—now called magnesium carbonate—and chalk (calcium carbonate). Black observed that when magnesia alba was heated or combined with an acid it began to bubble and left behind a residue. Black was able to use an analytical balance that he invented to precisely weigh the residue and note that it lost a noticeable amount of weight. Black hypothesized that the bubbling and weight loss was caused by the liberation of a gas that had been "fixed" in the magnesia alba (hence the name, fixed air).

[2]Black was likely not the original discoverer of the substance. It had been briefly described around 100 years prior by Jan Baptist van Helmont who called it gas sylvestre although Black was likely the first to describe its properties in detail.

Black was curious about the properties of this fixed air and so began to devise ways to experiment with the substance.

He noticed that it had an unusual effect on fire, noting that:

> I mixed together some chalk and vitriolic acid. . . The strong effervescence produced an air or vapour, which, flowing out at the top of the glass, extinguished a candle that stood close to it; and a piece of burning paper immersed in it, was put out as effectually as if it had been dipped in water. (West 2014, L1059)

This indicated that fixed air was not the same as atmospheric air. There were other unusual properties as well. He investigated the effect of fixed air on animals and found that it was remarkably toxic when inhaled — he noted that "sparrows died in it in ten or eleven seconds" (Robinson 1803).

The toxicity of fixed air when inhaled led Black to suspect that fixed air might be the air expelled as part of the respiration process itself. He designed several experiments to test this hypothesis. In one he blew bubbles into a solution of limewater (calcium hydroxide) and noted that a precipitate of chalk was leftover indicating that he had succeeded in fixing the air back into the chalk. He repeated this experiment on a larger scale by placing limewater soaked in rags in an air duct in the ceiling of a church and observing a chalk residue as the lime soaked up the fixed air from the congregation's respiration (West 2014, L1059).

He made several other discoveries about the substance and explained various observed phenomena. For instance, there was an observed unusual effect at the Grotto del Cano in Italy, where animals that visited the Grotto died, but humans could visit unharmed. Black explained this phenomenon by proposing that fixed air was heavier than atmospheric air and thus sank closer to the ground, poisoning animals but not humans. He also discovered that fixed air was emitted during the fermentation process (West 2014, L1059).

We now know "fixed air" as carbon dioxide, and Black's work isolating and describing the properties of carbon dioxide represented the first demonstration that gases can be weighable constituents of solid bodies, the first demonstration that gases are unique chemical substances and not atmospheric air in different states of purity, and the first demonstration that respiration involves the transformation of gases. In the 18 years after the publication of Black's work all the respiratory gases were isolated and characterized with Henry Cavendish discovering hydrogen in 1766, Daniel Rutherford isolating nitrogen in 1772, and Joseph Priestly isolating oxygen in 1774 (West 2014, L1059).

Joseph Black's work in isolating and describing carbon dioxide contributed significantly to scientific progress in chemistry. In much the same fashion as Galvani and Volta, Black discovered a new phenomenon and developed unusual and creative methods to study the phenomenon. In particular, his insight that carbon dioxide was connected to respiration allowed for rapid progress in isolating the other gases involved in respiration. As other scientists investigated new gases they attempted to explain them in terms of ultimately incorrect, yet sometimes useful theories. Indeed, even Black's theory that the air was "fixed" in the solids is somewhat different than the modern understanding of the phenomenon. In modern nomenclature, Magnesia Alba is MgCO3, and by heating it MgCO3 becomes MgO + CO2. We might say that carbon dioxide can be liberated from Magnesia Alba but in modern terms, we probably wouldn't describe carbon dioxide as being "fixed" in the Magnesia Alba. While Black's theory of carbon dioxide may not match our modern understanding, he nevertheless contributed significantly to scientific progress by isolating and cleverly studying a new phenomenon.

As additional gases were isolated and described, there was considerable disagreement about what the gasses were and scientists advanced a number of competing theories to explain their properties. For example, Rutherford and Priestly's discoveries were both explained in terms of the then popular phlogiston theory of combustion which posited that an element called phlogiston was released from materials as they combusted and combustion would continue until either all the phlogiston had been released or the air was saturated with phlogiston such that it could not contain more. On this theory nitrogen was labeled "phlogisticated air" and oxygen was labeled "dephlogisticated air."[3]

The debate over the nature of these newly discovered airs culminated in the work of Antoine-Laurent de Lavoisier and what is often called the chemical revolution. Between 1775 and 1789, Lavoisier is credited with discovering the law of conservation of mass and a new theory of combustion, which explained combustion and acidic corrosion in terms of oxygen[4] and eventually replaced the phlogiston theory. Lavoisier's approach to chemistry built on Black's approach through its focus on weight, but utilized much more sophisticated and elaborate equipment to investigate the properties of the newly discovered airs (West 2014, L1060).

3. Identifying a Phenomenon

The research efforts of Volta and Galvani, Galileo, and Black appear to have a number of attributes in common.

They feature a relative absence of established theories and well-understood instruments in the area of investigation, the appearance of strange or unexplained phenomena, and lack of theoretical and practical consensus among researchers. Progress seems to occur despite (and sometimes enabled by) flawed theories, individual researchers use imprecise measurement tools that are frequently new and difficult to share, and there exists a bi-directional

[3] Rutherford's initial name for nitrogen was "noxious air." Labeling it phlogisticated air is often attributed to Priestly.

[4] Indeed, the name "oxygen" comes from the greek roots (oxys) meaning "acid" and (-genēs) meaning "producer."

cycle of improvement between increasingly sophisticated theories and increasingly precise measurement tools.

For example, consider Black's study of fixed air. He began with an unexplained phenomenon: certain substances losing weight when heated. His approach to studying that phenomenon involved a wide range of methods, such as blowing bubbles into limewater and leaving limewater-soaked rags in the air duct of a church. This led to a larger study of new gases, where there were many theoretical disagreements between researchers, and where flawed theories (e.g., the theories of phlogisticated and dephlogisticated air) seemed to aid the process of discovery. Finally, improvements in measuring the weight of substances allowed for better theories and refinements to the researchers' instruments.

These examples gesture at the potential existence of a recognizable cluster of discovery-related attributes ("Attribute Cluster 1") that plausibly play an important role in scientific progress. This is striking, because this is different from another attribute cluster ("Attribute Cluster 2") that is more familiar and more commonly referred to, that appears throughout the history of science. That second cluster includes: large groups of scientists working together, a foundation of largely accepted theory, precise and well-understood instruments, researcher consensus on the quality of these instruments, and many small discoveries that tend to build iteratively on one-another and cohere with previous theory.

This raises a number of questions: Are the attributes in Attribute Cluster 1 actually present in cases described above? Do those attributes appear in a special set of cases in the history of science? More generally, is there a natural cluster of discovery-related attributes in the conceptual vicinity of Attribute Cluster 1 that appear in important cases of scientific discovery, like those described above? What can we learn from investigating the cases that are the most natural candidates for exemplifying attributes from Attribute Cluster 1? Is the distinction between Attribute Cluster 1 and Attribute Cluster 2 useful in the context of describing the progress of science?

The pattern suggested by the cases described above, and those like them, is noteworthy. If there is in fact a recognizable cluster of discovery-related attributes that plausibly play a role in scientific progress other than Attribute Cluster 2, this could be important for understanding when and how new fields make scientific progress. We believe this possibility is rendered at least somewhat plausible by the cases above and deserves further study.

4. Hypothesis

The cases of Volta and Galvani, Galileo, and Black illustrate a hypothesized pattern in the development of fields of science which we call "early stage science."

We hypothesize that:

1. Some scientific fields develop from initial investigations in nascent fields to highly functional knowledge acquisition programs.

2. The histories of the development of these highly functional knowledge acquisition programs are characterized by a similar, describable pattern.

3. As part of this pattern, the relevant scientific fields have different attributes at different points in their development. More specifically, earlier in the development of the relevant scientific fields, the fields have an attribute cluster in the conceptual vicinity of Attribute Cluster 1, as suggested by numerous examples. Some of those fields later have an attribute cluster in the conceptual vicinity of Attribute Cluster 2. The fact of these attribute clusters implies the existence of phases of scientific development.

4. These phases of scientific development arise from the facts about how people figure things out about the world. This includes how inference, experimentation, observation, theory development, tool development, and other aspects of how people can seek to understand the world around them lead researchers to be able to improve their understanding of a given phenomenon.

5. In accordance with this, researchers need to use different tools and practices depending on their starting state of knowledge. We expect to find that there is a coherent logic to the meta-practices that lead to the development and advancement of research programs under different starting conditions.

6. More specifically, a model of early stage scientific practice will explain how researchers overcome the difficulties that arise when attempting to gain knowledge when dealing with substantially unknown phenomena, poor tools, and so forth. When stated, this model will be both prima facie plausible and verifiable by checking against the research activities that led to important discoveries in practice.

It is consistent with the above hypothesis that many of the attributes specifically identified in the historical cases above are not actually constitutive of early stage science, so long as conceptually similar attributes can be identified which are.

5. Methodology

The current methodology of our investigation primarily focuses on analyzing historical case studies of scientific discovery in new fields. In this section, we cover how we plan to select and analyze specific cases.

5.1. Selecting Cases

To select cases, we will attempt to identify functional modern and historical scientific research programs and identify the initial discoveries integral to their development. By starting with functional scientific research programs and working back, we are aiming to ensure that the cases of early stage research we study are success cases. The pattern that we hypothesize to exist is not meant to be a pattern that occurs in all early stage research, but rather effective early stage research. Since the effectiveness of early stage research can be difficult to assess, we believe the safest set of cases to examine are cases where the relevant field developed into a full-fledged functional research program.

To identify functional modern and historical scientific research programs, we will look for fields where there are large groups of researchers studying similar phenomena, using very similar methods, with a corpus of shared theory, and substantial predictive power. This is our initial hypothesis of signs that will enable us to identify a sufficient set of functional scientific research programs. If we encounter reasons to change our criteria, we will do so, especially if doing so will help us to better identify successful early stage research cases. It is open to us, for instance, that we would be better served by looking at Kuhnian paradigms or broad scientific consensus, rather than looking for the attributes above.

Once we identify functional scientific research programs and identify the initial discoveries integral to their development, we will then analyze how researchers made those discoveries.

For example, consider modern astronomy. As part of doing their research, large groups of modern astronomers use highly advanced telescopes and highly advanced analytical methods to find, see, and study intergalactic objects at an incredible degree of precision. Astronomers have a shared body of theory, make the same observations with different telescopes, and are able to predict with high precision what they and others will observe when they look through telescopes at different points in the sky. These attributes indicate that modern astronomy is plausibly a highly functional scientific research program.

Having selected astronomy as a plausible success case for scientific development, we can then investigate the beginnings of the field to find plausibly important and formative discoveries. In this case, Galileo and others' work with early telescopes significantly changed how we both observe and think about objects in space. As a result, Galileo plausibly represents a case where successful early research methods might be visible and thus is fruitful to study.

5.2. Analyzing Cases

In analyzing the historical cases, we will be trying to build a coherent model of how researchers make scientific progress in the early stages of the development of scientific fields. We expect to approach this from many angles, looking at similarities and differences between cases, building causal models of the cases, and trying to state plausible general obstacles early stage researchers might encounter. By cross-checking the cases and the general model against each other, we hope to improve our models of individual cases as well as our general model.

This may or may not lead to convergence on a single, intelligible general model that fits the cases and also is plausible abstractly. If it does, we will consider this evidence in favor of our hypothesis. If it does not, either because plausible general models do not fit the cases or because the general models contain attributes that are not intelligibly related to the logic of discovery in the early stages of a field, we will consider this evidence against our hypothesis.

If we reach an adequately plausible general model, we will then investigate whether it can be used to generate recommendations for present-day scientists seeking to make progress in fields operating under early stage research conditions. If a particular model relies heavily on factors local to the particular historical case, researcher, or era, it may not serve as a good template for recommendations for present-day scientists or a general theory of scientific methodology. On the other hand, if a model tends to feature potentially generalizable methodological elements with mechanistic relations (e.g., a particular model for how instrument development works at different levels of theoretical uncertainty), we can see whether the model can generate recommendations for current researchers.

6. Conclusion

Following the methodology above, we believe we will be able to select and analyze cases of discovery that have led to the development of highly functional scientific research programs. We expect our analysis to help confirm or disconfirm the existence of early stage science as a unique phase of science with a unique and understandable methodology. It is our hope that investigating this hypothesis will shed light on what methods should be used to make scientific progress in new or underdeveloped fields, and thereby help push science forward.

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