THE SCIENCE OF SCIENCE EDUCATION (WITH A FOCUS ON THE PHYSICS OF MOTION): HISTORICAL, EPISTEMOLOGICAL, AND RESEARCH CONTRIBUTIONS

A REVIEW OF AND COMMENTARY ON LITERATURE

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Abstract

In an attempt to better understand the field of science education research, the field is reduced to three major contributing disciplines: the practice of science itself as informed through the history of science, developmental psychology and epistemological considerations, and finally the practice of education. To build an archetypal case, I look exclusively at dynamics, an early pursuit of physics; the lessons could be applied to other branches of science. In looking at scientific content, it is possible to learn more about the nature of scientific knowledge, and the representational tools that scientists use to generate new knowledge. This leads to the realization that science in itself is an epistemological tool and raises questions about human development. In development, we see the processes that individuals employ to gain new knowledge, scientific or otherwise. Development also provides mechanisms for communities to develop and utilize the same representational tools that are so valuable in creating scientific knowledge. Finally, the lessons of development must be translated into learning environments. This typically means classrooms. Here, researchers and educators have had to maintain a precarious balance between theory and practice, yet there have been several successful results suggesting with a clever approach, excellence in science education is an achievable goal.

Introduction

I have cycled through many possible introductions through this paper. All have met the same inauspicious demise, falling under the weight of my delete key to forever to disappear into the electronic ether. In place of my fallen words I am leaving this anti-introduction, a matter of fact statement of what I will set out to accomplish.

Science education is a common topic, and at the same time impossibly broad. Many agree to the importance of science education, though beyond that, it is difficult to pin down specifics. To that end, I set out to establish a sort of primer on science education. This meets my own needs in helping to develop my interests for continued research. It also provides a springboard to allow for future discussion. Guiding this paper I have identified four simple yet major questions that are of central interest.

(1) What is science (or, what are science's historical influences and how have these influenced the development of scientific knowledge)?
(2) What is the value of science education?
(3) What sort of epistemological theories are relevant to describing scientific learning?
(4) What pedagogies have worked in teaching science?

By design, these are broad questions with nuanced answers shaped by decades of previous research. The rest of this paper is dedicated to answering these questions. While the questions are interesting in isolation, it is within their relationships that it is possible to extend understanding of science education beyond a pure echoing of previous work.

These questions are not answered in the order they are presented here. I first look at the importance of science education, which I feel is undervalued in the context of the original ideals of public education. Most will accept an inherent value in science education *prima facie*. I am one of those people. However, I am not going to assume that everyone will join me on such a bold assertion. Others have thought about the role of science within an educational framework. By undertaking this exercise, we are forced to develop a philosophy for science education. This philosophy can take us to unexpected places, as the roles of science and politics intermingle. In short, my first task in this paper is to establish that science has a place in a greater educational framework. This requires backing up even further, and pondering why an educational framework exists at all.

Upon establishing that science can justify its existence on the educational landscape, I turn to defining science though it's history. This is necessarily a discussion on epistemology, since science is the creation of new knowledge. The case study for answering this question is the development of the concept of force. In unraveling the historical tangle of people and ideas, it is possible to see parallels to developmental theory and the behavior and thoughts of students in modern classrooms. In defining science through it's own history, we end up with the fortuitous coincidence of looking at a mirror of the growth of individual thought.

Epistemology is the study of new knowledge. Because science is the creation of new knowledge, the two discussions dovetail nicely. However, perhaps obviously, it is not just collections of scientists who generate knowledge. Humans develop a set of unique knowledge from their infant roots. From hapless little beings rise independent adults capable of phenomenal cognitive processes. This transformation is nothing short of miraculous. It also informs the processes people employ to learn scientific knowledge.

Epistemological processes and the practice of teaching are tightly intertwined, yet separated by the chasm that divides theory from practice. I draw a clear distinction between the epistemological processes that are employed and the actual practice of teaching and learning. Simply having an epistemological resource does little good without a framework to act upon it. Teaching and learning seek to set this framework in place. To finish up the paper, I take a look at a very small subset of the techniques that have worked in science education.

In answering the above four questions, I hope to pave a path that allows for a clearer understanding of science education. I seek to inform my own research ass I continue forward. However, it is my hope that this paper also helps frame some of the big questions in science education for others who either seek to make policy in regards to science education, or build new knowledge through their own research.

Part I:
Why Study Science Education?

The main objects of all science [are] the freedom and happiness of man.
Thomas Jefferson

I will start this paper off with a confession; I feel a little awkward adding my voice to the discourse on education. My focus is on science, which in itself seems an odd distinction to me. Why would one choose to focus on science? The modern academic curriculum is a crowded place. It is true; science plays a valuable role in my own life, as well as in the growth of society at large. However, the statement seems more vacuous when one considers others could repeat the same justification for literacy, math, or music. Ultimately, the only way to resolve this is to acknowledge that someone has to study science, and to recognize it's place in the larger educational framework.

This is still not completely satisfying for me. Consider the following unrigorous exercise. From 2000 to present, an academic search engine can find around 19,500 articles containing the exact words education reform. I did not read them all, I cannot vouch that they are about education reform, just that they contain those words in that order. The same search limited to 1990-1999 produces about 10,500 articles, and I employ the same caveat. The prior decade only produces 1,490 articles, and again I have only read the tiniest of slivers. The search engine does not do as well finding older articles, so I assume that the 1,490 number is a gross underestimate.

I have several interpretations for this phenomenon. First, without even defining educational reform, there is a lot of it. Education reform suggests some level of dissatisfaction with the status quo. However, with the perpetual reform that seems to be peddled, the status quo is a moving target at best. This is not necessarily a bad thing, even if every one of those 20,000 suggestions for educational reform works, a reasonable reaction is to simply point that is it is nice that the intervention worked, but how could it be even better?

A more reasonable expectation is that some percentage of those 20,000 articles is noise (unhelpful to either research or educational discourse), and the signal (the worthwhile discussions) must be teased out. The targets of the reform are educators, and they are asked to filter the signal from the noise. Yet even the most consummate professional cannot be such a filter in the face of increasing amounts of information. This is still maddening to me. At the beginning of a career, I know I am joining a cacophony 19,500 strong. Whatever this reform is, I am telling educators they need more, and after listening to all the previous calls for change, they should listen to one more.

The next three parts of this paper attempt to frame the practice of science education in its historical roots, theoretical epistemological and cognitive obligations, and research tradition. This look frames my future research. But before these discussions, I am obliged to justify that such a focus is worth the effort, and describe a philosophy of education that has room for science and science education research.

Education is a political endeavor, since any choice made, any allocation of resources (the most valuable of which is time), reflects one set of values over another. Advocating one set of educational values is a serious responsibility, and while there are many places to look for inspiration, I turn to Jean-Jacques Rousseau, an 18th Century philosopher whose voice among many helped lay the groundwork for revolution in the North American colonies and France through the creation of the idea of a social contract.

The problem is that the ideas in Rousseau's *Emile* (2004), originally published in 1762, where he outlines his thoughts on education, were roundly criticized both by his contemporaries and modern scholars alike (e.g. Noddings, 1995). Rousseau separates the natural man from the social man, and sees man as happiest in his natural state. This precludes social structures like the church (which got the book banned), but also social innovations that would be afforded by science. I will conveniently ignore this hiccup for the time being. He also suggested radically different schooling based on gender, and I am ignoring that as well. (I can selectively ignore these facts because Rousseau's *Social Contract*, a far more influential publication, helps start a process that will eventually get society around these bumps.)

Rousseau sees education as a relationship between a teacher and a student. The student, in the natural state, must learn how to participate in the social world; the teacher is a guide. The teacher in the mode of cultural gatekeeper makes decisions about what would best inform the student. In Rousseau's romantic language, these are things of beauty and elegance. Allowing for some deviance from Rousseau's doctrine, this carves a place for science education to enrich both society and the individual. Rousseau understood that 'natural man' was an ideal; in order to achieve the highest potential one must exist within a society. This society will clearly benefit from scientific innovation, a simple truism that finds backing in modern economic thought (M. P. Feldman & Audretsch, 1999). But exploring the physical world provides a connection back to nature, and allows for a certain elegance that can be an intellectual end unto itself for the individual.

Emile is merely a starting point, not an end point. There are too many concerns with the philosophy it presents. However, it provides an intertwined view of the individual and the society, giving context to a philosophy of science education.

In further refining a philosophy of science education, it makes sense to back up and ask the question: what is science? This is a very old question, but the trite summary is that science is systematic knowledge of the physical world. Kimball (1967) lists eight characteristics of scientific knowledge, while beginning a tradition of research comparing student views of scientific knowledge to that of practitioners.

(1) The fundamental driving force of science is curiosity concerning the physical universe. It has no connection with outcomes, applications, or usages aside from the generation of new knowledge.
(2) In the search for new knowledge, science is process oriented, it is a dynamic, ongoing activity rather than a static accumulation of knowledge.
(3) In dealing with knowledge as it is developed and manipulated, science aims at ever-increasing comprehensiveness and simplification, emphasizing mathematical language as the most precise and simplest means of stating relationships.
(4) There is no one "scientific method" as often described in school science textbooks. Rather, there are as many methods of science as there are practitioners.
(5) The methods of science are characterized by a few attributes which are more in the realm of values than techniques. Among these traits of science are dependence upon sense experience, insistence on operational definitions, recognition of the arbitrariness of definitions and schemes of organization and classification, and the evaluation of scientific work in terms of reproducibility and usefulness in furthering scientific inquiry.
(6) A basic characteristic of science is a faith in the susceptibility of the physical universe to human ordering and understanding.
(7) Science has a unique attribute of openness of mind, allowing for a willingness to change opinion in the face of evidence, and the openness of the real of investigation, unlimited by such factors as religion, politics, or geography.
(8) Tentativeness and uncertainty mark all of science. Nothing is ever completely proven in science, and recognition of this fact is a guiding consideration of the discipline.

Kimball's list is not perfect, but is functional, eliminating the need for distinctions in abstract between different branches of science, such as physics, biology, or chemistry. While these disciplines concern themselves with different types of natural phenomena, all of these phenomena are natural, and as stated earlier, classifications are necessarily arbitrary (which leads to blurred areas of study like biophysics or organic chemistry, etc.).

Kuhn's (1970) treatment of the growth of scientific knowledge is a modern classic, and describes in great detail the mechanisms behind Kimball's second point. Rather than proceed in orderly transition, as perhaps suggested by the idyllic seventh point, scientific knowledge is subject to profound and perhaps violent revisions. Kimball's fifth and sixth points are fascinating, and sometimes downplayed, since they demand the presence of a specific scientific culture. Roth and Lawless (2002) have noted this point, in the context that cultural knowledge has a well-studied framework for transmission. However, ascribing an element of faith to the scientific process emphasizes that there is no preordained reason for the universe to be understandable or subject to human organization.

To consider the original task of defining science to be complete would be a mistake. The philosophy of science and structure of knowledge has been a viable framework for study since at least St. Thomas Aquinas, if not much longer. Rather, this minimal framework simply serves as a place keeper to introduce consensus on the characteristics of science.

Having successfully (if modestly) defined science, it is possible to continue to search for its role in greater society. Education represents a form of investment, and must produce some sort of value to society at large. Rousseau printed a far more influential book than *Emile*: the book *On the Social Contract* (2007), first published in 1762, described the pact that an individual must form with society. This reflects the philosophy that has already been discussed: man is happiest in his natural state, with unlimited *liberté*, but achieves his full potential in a social environment.

The definition of liberty must be treated so carefully that I refer to it in Rousseau's native French. *Liberté* is used to distinguish between a contemporary, sloganeered definition of liberty, which in contrast with *liberté*, can apparently be packaged up and exported. *Liberté* is intrinsic to man, and a certain amount is surrendered when entering into a social contract.

These thoughts profoundly influenced Thomas Jefferson, a late 18th Century political philosopher and the third President of the United States. Jefferson was prominent in a group that set out to establish the radical political experiment that would become the United States of America, moving away from the monarchy-style governments that were still prominent in Europe. A tea part and a war later, a representative democracy was founded. The goal was simple: ensure a maximum amount of *liberté* by establishing a system of self-governance. In the purest formation of the Jeffersonian democracy, it was assumed people would consent to a minimal amount of governance, leading to a weak central government. The alternative of the day was Alexander Hamilton's vision, which demanded a stronger central structure. The nuances of this debate still live on, but for my purposes are simply tangential. Regardless of the fine structure, a government that functions by consent of the governed has implications for education.

Jefferson understood that in his experiment, he would need a well-informed public and in 1779 proposed the creation of public education in Virginia.

> Whereas it is generally true that the people will be happiest whose laws are best, and are best administered, and that laws will be wisely formed, and honestly administered, in proportion as those who form and administer them are wise and honest; whence it becomes expedient for promoting the publick happiness that those persons, whom nature hath endowed with

> genius and virtue, should be rendered by liberal education worthy to receive, and able to guard the sacred deposit of the rights and liberties of their fellow citizens, and that they should be called to that charge without regard to wealth, birth or other accidental condition or circumstance.
>
> (Jefferson, 1893, p. 221)

Jefferson's democracy was and remains an experiment where individuals are responsible for their own governance. In order to prepare individuals for such a responsibility, Jefferson felt it was the duty of the government to educate all of it's voting citizens. With the benefit of time, this vision came to be more inclusive.

In further discussing the role of education in the new government, Jefferson described his values of knowledge. He had particularly high regard for scientific knowledge, seeing it as essential for the advancement of both society and the individual. In agrarian society of the late 18th and early 19th Centuries, or in modern times, science was and is a vehicle for empowerment. There are many ways an individual could use science to increase quality of life, though in agrarian North America, it might resemble techniques to improve crop yields. Today, there are so many applications of science it is a fruitless exercise to elaborate further on how science could effect quality of life.

More important to Jefferson, however, was how these individuals would be able to make decisions about their government. Science affords a certain system of thinking, predicated upon a system of logic and information. Possessing a command of scientific thought would allow an individual to make rational and informed decisions about the future direction of the future of government.

Over a century later, John Dewey would elaborate on the role of education within a democracy. Dewey saw an educational system that exists to enrich society. Like Jefferson, he saw the future of his republic as dependent on a well-informed public. Society as a whole would be happy with a complete education, as individuals would be best prepared to carry out the critical thought required to make choices and lead independent lives in a democratic government.

Dewey also carved a special space for scientific knowledge, claiming "Without initiation into the scientific spirit one is not in possession of the best tools which humanity has so far devised for effectively directed reflection" (Dewey, 1916, p. 223). Dewey was not interested in highlighting a single scientific content, and had a disdain for curriculum that focused on memorization of scientific facts over knowledge of scientific processes. With a command of scientific processes, he reasoned, one would be well prepared for addressing new problems. Like Jefferson, he saw this as an essential skill to a functioning democracy. Charged with self-governance, people will be happiest when making decisions based on sound reasoning principles, backed up by a scientific methodology.

Dewey and Jefferson advocate science as a path to epistemological skills. These skills describe ways to acquire new knowledge, and not necessarily an ability to parrot previously discovered scientific ideas. In the sphere of modern educational thought, Hammer (2000) discusses student epistemological resources as being vital to a successful science education. These epistemological resources are metacognitive skills, being able to break down a problem, and critically think through a given scientific problem. Hammer's work with high school students demonstrates that when students develop epistemological beliefs consistent with practicing scientists, they develop a strong conceptual understanding of scientific content—they understand material on a qualitative level. However, these epistemological beliefs are also the same ideas that lead to science being so highly valued in political philosophy. They support independent and critical thought driven by evidence, vital cogs to a participatory government.

That a scientifically literate population is the one best prepared to engage in a participatory democracy is certainly a powerful motivation for engaging in quality science education. However, there are other potential benefits to a society that has a population well versed in science. The traditional argument along this line can be simply made. Conversation with individuals of two generations past will reveal a starkly different world, where many of the commonplace contraptions that pervade daily life simply did not exist in decades past.

Innovation could be described as the sum of new knowledge created in a given interval of time (crudely quantified as $\int K dt$, where K is an otherwise unspecified function for knowledge). Assessing its value is a rather interesting quandary. Magnell (2006) takes a philosophical tact, first eliciting "the tragedy of the commons." In his specific example, antibiotics are almost always a positive treatment path for an individual. However, society as a whole suffers as bacteria develop increased resistance. The choice becomes one of morality, as a doctor can select a treatment that benefits the individual to the detriment of all others. Magnell refers to this as collapsing goods, and outlines four ways to address the problem. The preferred method is one of innovation, presented as the best moral outcome. This helps the individual, and solves the societal problem. Magnell's parable considers the turn of the 20th century transportation problem, as horse waste was becoming a major burden in urban centers. A transportation innovation allowed for freer access to both public and private modes of transportation, washing away the old problem. New problems with current transportation models demand a new innovation, which will have the same hypothetical benefits to individual and society alike.

I am a little nervous relying too heavily on questions of morality, simply because morality is not mine to decide (or, put differently, if roles were reversed and I were a reader looking at any claim of moral authority, I would be very skeptical of such a claim). Another way to quantify the benefit brought through science education is by measuring economic progress. Lucas (1993) discusses the Korean economic 'miracle' (economists' definition of miracle is simply a set of fortuitous events ripe for case study, as national-scale controlled experiments are off the table). He makes a direct comparison to the similar situations of Korea and the Philippines in the 1960s, and how their subsequent fortunes are linked to diverging levels of societal scientific literacy.

In concluding what led to this dramatic difference between the two nations, Lucas offers the following conclusion: "The main engine of growth is the accumulation of human capital—of knowledge—and the main source of differences in living standards among nations is differences in human capital." Economic language is cold, but there are conclusions of particular nature of this 'human capital.' Lucas points to 'knowledge spillover' from increasingly technical jobs, using knowledge spillover to signify a local populations increased knowledge and ability to apply it to novel situations. In other economic literature (e.g., Howells, 2002) knowledge spillover is considered to be a possible driving force of innovation (with caveats, see Breschi & Lissoni, 2001). Education with a stated goal of increased scientific literacy will augment this 'human capital,' facilitating these types of beneficial spillovers and providing more motivation for quality education.

Paulo Freire (1970/2000) discusses how education can impact freedom, his version of personal *liberté*. Freire sees education through the lens of the oppressed and the oppressors. The oppressed are people who have lost their freedom, and in turn lost the authenticity of their human experience. While the problem is epidemic across the social sphere, the solution to the problem is a co-construction of a new pedagogy for liberation between the oppressed and the oppressors.

Freire also illuminates the complicated relationship between the individual and the community in which he inhabits. In his first work, *Pedagogy of the Oppressed* (1970), there is an emphasis on individual pedagogies that can lead to liberty. However, Freire's liberty is never a personal one. He writes from the perspectives of entire societies falling victims to oppression. His goals, made clear in later publications (e.g., Freire, 1976) are the liberation of entire communities.

However, despite the emphasis on community-wide goals, each individual constructs a unique pedagogy. The model follows a specific approach to cognitive psychology, which suggests that individuals construct their understanding of the world. By embracing such a strategy, each pedagogy is unique, a celebration of individual differences as the key to community empowerment. For Freire community empowerment and personal *liberté* are entirely inseparable.

Freire's ideas are about education in the abstract, though have relevance to science education. Zahur, Calabrese Barton, and Upadhyay (2002) quote a teacher educator in Pakistan:

> Teachers should teach science to empower students to be more involved in social change because, for me, it should be the ultimate aim of education. I have seen parents and people around listen to children a lot. Even initiatives at home empower parents and enable them to feel proud of the fact that they are learning something from their children or she/he is becoming so concerned about the environment. The same thing goes out in the community. The whole street and community would appreciate it and this political change will empower the whole community. (p. 900)

The teacher grants this interview from Pakistan, a poverty stricken region of the world. Further, the country is marked by both a caste system and very different ideas about gender quality than Western countries. Under the lens of Freire, these people are not free.

The quote also demonstrates why the solution must be local, and must involve the oppressed. It is rather trivial to state that those in Pakistan face Pakistani problems. Freire's insight is that those oppressed must take ownership of their education in order to find freedom. Imposing an external set of values only leads to more oppression. In this case, the teacher relates how science education can teach about water quality in areas where there is heavy upstream pollution. This empowers local people to take charge of their situation, yet outside oppressors would not be able to enter the situation and acutely address their needs. Such a thing can only be done in tandem between the two groups of people.

One does not need to span the globe to find a need for personal empowerment through education. Moses and Cobb (2002) take the stance that algebra is a civil right. They note that the subject has become a gatekeeper topic, and without its mastery, individuals are locked out of higher mathematical tracks, even if the course material has little actually to do with algebra. Further, a mastery of algebra is a prerequisite for the coming generation of children, necessary for meaningful participation with wider society.

Science education cannot honestly be put on the same pedestal. As of right now, there is no gateway effect with any individual science course (i.e., physics, biology, or chemistry), yet on some level the arguments loop back to Jefferson and Dewey's thoughts. While mastery of one scientific discipline may not be necessary, the reasoning processes afforded by scientific thought are more necessary than ever. In the same way that Moses and Cobb see access to the content of algebra to be an innate civil right, we can see access to the methods and epistemology of science to carry the same weight.

Part II:
The Role of Content and a Historical Perspective

Science encompasses an endless set of domains. Through high school, most people are aware that things called physics, biology, and chemistry exist, and are different areas of study within science. Even within this taxonomy, there are countless sub-domains. An introductory physics curriculum will cover classical mechanics, electricity and magnetism, and if the student is lucky, a brief introduction to modern physics. Even these areas of study are hopelessly general; it is endlessly possible to further narrowly define scientific study.

Every sub-domain of scientific knowledge offers a new opportunity for science education, to 'stand on the shoulders of giants,' as Isaac Newton put it. I have no intention of fiddling endlessly with every possible content area in science education. For the sake of a meaningful narrative, it is necessary to select one piece of content and take the discussion from there. Here, I choose to focus on physics, and when necessitated due to overlap, astronomy.

Physics and astronomy are two very old sciences. One of the oldest documented inquiries is the study of how objects move, the study of kinematics. This is an ideal content to explore. Aristotle wrote down his thoughts on the matter, and in the interim three millennia since, a variety of scientists have tackled the subject. Even a seemly rock-solid classical theory has found its share of problems; the topic is not exactly dead. Within these series of intellectual problems, each a cognitive obstacle, there is an opportunity to explore the crevices of human thought. Content in genesis provides a paper trail of trial, error, and cognitive motion, a perfect vehicle to provide insight into how we might expect people to think about the problem. This perspective has history in the literature of psychology (e.g. Piaget & García, 1989), and will be explored further.

Further, science educators have been stymied by an apparent lack of student understanding of kinematics, and the related field of dynamics. Curiously, these students have adopted conceptual positions similar to their historical counterparts, implying a certain value in understanding the history of physics. Ultimately, physics educators strive to impart a Newtonian understanding of physics, but shaped by the knowledge of the historical ebb and flow, students' initial ideas can be seen not as wrong but as particular modes of reasoning.

The well-documented history and educational concerns make kinematics and dynamics an excellent prototype for studying and exploring science education. Beyond this, these disciplines came face to face with astronomy in a well-documented example of how scientific abstractions can change the way an entire community thinks about the world. The advent of (now) classical mechanics meant that geocentric theory had to be abandoned, and conceptual change proved to be a violent undertaking. This is a poignant example of how a scientific outlook can change one's capacity to understand the world.

This section describes the science of motion from a historical perspective. It provides a brief summary of the problem of motion. In order to make sure that all readers are on the same page, I discuss some of the major scientific concepts within motion[1]. From there I discuss the history of the problem of motion, working through four major eras. These are Aristotelian, medieval, Renaissance, and Newtonian/classical. Those familiar with the content will realize that this leaves out modern ideas, and may object, since both Einstein's ideas and quantum mechanics are interesting for their startling nature alone. The reason this fifth era is mostly omitted is because, simply, it is not possible to talk about student education in the same way. For better or worse, not nearly the same volume of students are learning modern physics, so discussing it in any detail does not provide the same prototypical example that classical mechanics provides.

Finally, the history of motion holds a central place in physics, precisely because it demonstrated the power of rigorous scientific theory. There are many complete and fascinating books written on the historical scientific discourse and the major actors involved. These next several paragraphs will not strive to join their ranks, simply to provide context for a larger discussion on education.

II.1 An Overview on the Science of Motion

Motion is a daily part of the human experience. It is natural to want to be able to describe and understand this ubiquitous phenomenon. Imagine throwing a small rock. As it leaves your hand, it traces an arc, constantly slowing down and eventually crashing into the ground. The entire exercise seems very simple and the explanation for how it occurs seems rather straightforward. The problem, however, is not trivial.

A discussion on motion pre-supposes a certain amount of knowledge of modern physics. It is not my intention to write a physics text book, but a quick reflection of the factors that are measured in motion will aid in understanding some the historical developments in understanding the development of

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[1] As a qualifying paper (QP), some of my audience will command elementary kinematics and dynamics quite well, and skipping a rudimentary presentation of Physics 1 content will not hurt their understanding. That said, their thoughts are always appreciated. If the paper finds life beyond a QP, then it is probably worthwhile to carefully define Newtonian physics.

force. There are two fundamental quantities at issue: space and time. Space is measured as displacement, the distance between one point and another. Time is measured in a similar manner; it is a temporal displacement is a measurement of one time to the next. These two quantities were measurable in all time frames discussed by this paper. Velocity is a the relationship between a change in time between a change in space, and more elegantly written as $d\mathbf{x}/dt$. Acceleration is the relationship between a change in velocity and a change in time, and succinctly written mathematically as $d^2\mathbf{x}/dt^2$. Thus, in imagining a kinematics description of the aforementioned rock, we would describe its change in position over a measured time interval. To describe the acceleration, we would measure the change in a velocity over the same time interval.

A complete, mathematical description of the flying rock scenario, and any system of motion remained unpublished until 1678, and the author, Sir Isaac Newton of Cambridge, England, was rewarded with scientific immortality and near universal recognition. Newton added another dimension to the kinematics analysis by including force, which he defined as being proportional to the acceleration, or change in velocity with respect to time. This is not an intuitive leap, despite its utility to daily life. Testament to this was that Newton's solution lay undiscovered until the Age of Reason, a relatively recent era on a grand timeline, despite the efforts of countless brilliant minds that preceded him in directly approaching the problem. There is a hypothetical sidebar here on the remarkable nature of any scientific discovery. Like any physical phenomena, a description of motion is indiscriminately accessible to anyone who entertains and thoroughly explores it. If motion could be understood on an intuitive level, then Newton would not be predated by millennia of alternate descriptions of motion. Educators would not struggle to facilitate students' learning of his ideas.

To understand historical conceptions of force and motion, the best place to start is at the end point. This is a little tricky to explain within the narrative, since every instinct within education steers me away from a didactic explanation. Further, mechanics is the subject of textbooks, including the treatise that Newton himself wrote. A two-paragraph explanation of the concept of force seems woefully insufficient. With that in mind, here are Newton's Laws in his own words:

Law I.

Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon.

Law II

The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

Law III

> *To every action there is always imposed an equal reaction: or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*
>
> *(Newton, 1995)*

The first law is a statement of inertia. It makes the rather rudimentary claim that an object at rest will remain so, which is easy to imagine in one's mind's eye. If the scaffold is helpful, picturing oneself on a frozen lake could be useful. The second part makes the claim that an object moving on a 'right' (straight) line will retain its motion. Combined with the second law, this is a drastic change from the theoretical frameworks that came before Newton.

Sliding upon the frozen lake, one would continue in motion for a long time. It is possible to imagine scenarios where the motion could be retained for even longer periods of time, for example by putting on a pair of ice skates. This has the effect of reducing the frozen lake's ability to resist one's motion. If this could be reduced indefinitely, one could eventually reach the point where the motion never stopped. This would require the removal of not only the frozen lake, but also the air around it, but unimpeded motion would continue indefinitely.

The second law speaks about change in motion requiring the action of a given force. On the frozen lake, both the friction of the lake and water serve to impede motion. The reaction is that of slowing down. The force is applied constantly (while the skater is moving), and thus the slowing down continues to occur until the skater reaches a complete stop. As Newton says, the change in motion is in the same direction as the applied force. The example ice skater always has force applied opposite the direction of movement. But the force can also be applied in the direction of movement, in which case the object in question would speed up (think of a falling object). Or the force can be applied in some other arbitrary direction relative to motion, which would require a more careful treatment.

The first and second laws speak of similar phenomena, but the third law brings up something different. It is usually summed up as 'equal and opposite.' If a force is impressed on an object, then the object impresses the same exact force in reverse. The consequences of this can be puzzling—if a large truck strikes a compact car, then the contact forces are 'equal and opposite.' This can be verified, though a treatment here would be tangential. Educational data suggests that this is the last aspect of Newtonian understanding that a student will reach (Thornton, 1997; Thornton & Sokoloff, 1998) a fascinating finding on its own that demonstrates how stubborn the human mind can be when asked to abandon thoughts that seemingly violate common sense.

One perhaps obvious element of the description of motion is that it encapsulates a phenomenon that unfolds on a wide variety of scales of distance and time. The flap of a hummingbird's wing is an example of frenetic motion, while the precession and recession of glaciers is an example of languid motion. Neither of these examples is particularly extreme in the scale of the universe, yet they test the limits of human perception. However, motion also encapsulates a runner's sprint or the fall of an apple; these are time and space scales easy for a human to grasp. One of the attractive elements of Newton's theories is that descriptions of motion are equally valid regardless of scale. One who masters the tools to describe a falling apple is also mastering the tools to describe an orbiting planet. Motion, therefore, can be understood and learned on a scale that is approachable from the human experience.

These relationships pave the way to a classical understanding of motion. They were first published late in the 17th Century, many, many millennia after the problem of motion was first apparent. The fact that the solution to an everyday problem can remain opaque for such a huge period of time makes the finding immediately interesting as a case study in human cognition.

II.2 Pre-Classical Physics

As a study in cognition, one must look back at the motion problem from the perspective of pre-17th Century physics. There were a variety of ideas that have been exhaustively studied by historians. In this context, only a survey is presented as relevant to looking at scientific development as a model for personal intellectual development. Further, others have explored the ground covered by this survey (e.g. Cohen, 1960). There is a common thread in history of science literature to tell the story of a torch passed from Aristotle; to various medieval scientists; to enlightenment figures Copernicus, Kepler, and Galileo; then Newton; and finally Einstein[2] (see (Stinner, 1994), who approaches the problem from an educational perspective though this treatment omits Renaissance and Enlightenment figures beyond Newton and discards the role of astronomy; (Piaget & García, 1989), who approach the problem from a developmental perspective; and of course (Kuhn, 1970)). While this presentation is a simplification, the thought processes of each of the scientists were unique and, as will later be clear, show up everyday in modern physics classrooms.

II.2.1 Aristotelian Physics

The first philosopher credited (at least in Western Society) with a systematic approach to the study force and motion was Aristotle, the ancient Greek philosopher who contributed much to the ideas underlying all of Western civilization. For our purposes, there are three major contributions that need to

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[2] The relevance of Einstein, relativity, and quantum (in total, 'modern') physics to developing a Newtonian understanding of physics could be debated to interesting ends. On one hand, an instructor should know where future physics instruction will lead the students. It would add richness and depth to the material that might not otherwise be present. On the other hand, from the student's perspective, this adds another layer of material that is, on the surface, even more conceptually demanding. As has been mentioned previously, the discussion in this QP leaves aside modern physics; the goal here is to understand the historical development of Newtonian conceptions.

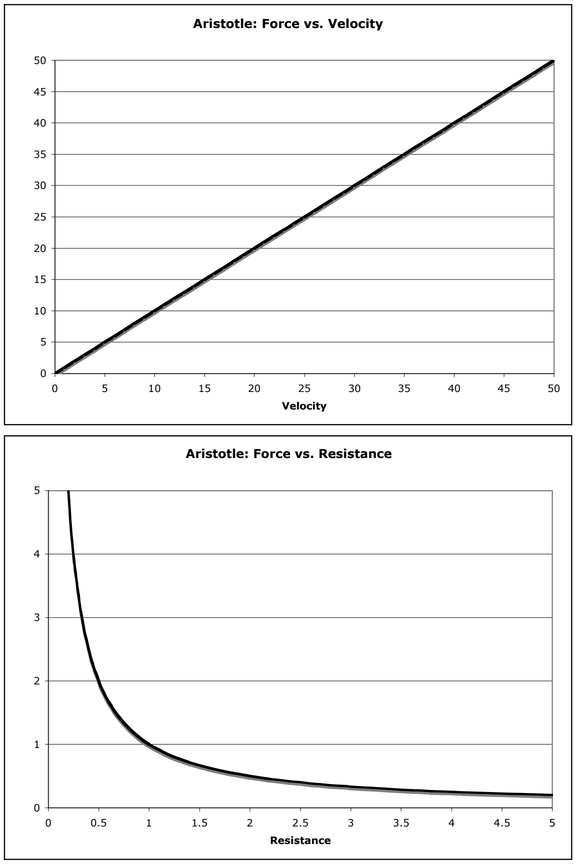
be examined. First is an approach to thinking about objects moving on the Earth; second is the approach given to objects moving in the heavens; and third, a short summary of Aristotle's entire world view.

Aristotle's model of force can be reduced to the relationship:

$$F \propto \frac{V}{R}$$

(Stinner, 1994)

Conceptually, this makes force a function of both a moving object's velocity and the resistance acting upon it. One could increase force by either increasing velocity or reducing resistance. Doing the opposite would have the effect of decreasing the force. There is an immediate theoretical problem: if the resistance becomes zero, the force becomes infinite. Of course, Aristotle's lifetime spanned 384-322 BC, traveling to the stars was not a likely proposition, and Aristotle held a worldview that would make such a trip a silly proposition in any event. In Aristotle's universe, zero resistance did not exist and therefore neither did the theoretical hiccup. From Aristotle's perspective, his model is internally consistent.



Aristotle: Force vs. Velocity

Aristotle: Force vs. Resistance

Figure 1: Aristotle's Theory of Force. These graphs represent Aristotle's theory of force. Force is directly proportional to velocity and inversely proportional to resistance. This type of representation is far more modern than Aristotle, as this style of graphing was developed in the 18th century,

Worth noting is that in this model, force, like velocity, appears to be a property of the moving object, an internal construct which slowly dissipates as the object loses velocity. Ioannides & Vosniadou (2002) point out that this is a model of force that students will spontaneously adopt; in this sense, Aristotle's point of view is well alive in the classroom. However, some care must be taken in comparing students to great minds from the past. It has been pointed out that students do not display the same level of reasoning or internal coherence that defines Aristotle's theories (Lythcott, 1985). That can be extended even further, to make the broad claim that most students do not reason as well as some of the finest thinkers from the past three millennia. This is not an indictment of the students, but does limit the extent to which a comparison can be made.

The Newtonian perspective, from here, is a good deal different. Force is impressed on an object from an external agent. Simply knowing an object's velocity will provide no information about force. What matters is the change in velocity. At this point in history, a good deal more work was required in order to establish a better model. The same can be said of a student who exhibits Aristotelian-like ideas about motion.

Another key aspect of Aristotelian physics is its view of the heavens. On the surface, this seems unrelated to the story of force and motion, though this is not completely the case. Newtonian biographer Gleick (2003) relates a story about the origin of the *Principia*, the book that outlines Newton's studies and findings of force and motion. In August of 1684, Edmund Halley met Newton in his Cambridge home. They discussed pressing issues in the physics of their day, the paths of planets, and the role that gravity might play. However, at this point gravity was an entirely nascent subject, Gleick goes so far as to credit Newton with its 'discovery.' Halley asked Newton what path the planets would curve if they were affected by some force that worked with an inverse square rule. Newton countered that the path would be an ellipse, and that he had solved such a problem earlier, but could not produce the calculations. In 1886, the Principia arrived. "[A] Mathematical demonstration of the Copernican hypothesis," Halley told his colleagues (Gleick, 2003). Newton's laws don't simply describe the motion of projectiles on the Earth. The laws describe the motion of all objects on all distance and time scales (ignoring advancements of the past century). There is no inherent reason why motion on the Earth and the motion of the heavens should be governed by the same principles, but as Haley's quote illustrates, Newton's theory provides an elegant unification for describing motion, independent of context.

Understanding motion of the planets is a key part of the force and motion narrative, so it is completely relevant to consider the Aristotelian position. Greek scientists were active in astronomy, and a healthy collection of individuals made contributions (Goldstein & Bowen, 1983) to the field. Yet, the Aristotelian universe is the well-known geocentric model. The same model was refined by Ptolemy in the second century AD, and carried forward with that name: the Ptolemaic universe. Yet when Galileo (Galilei, 2001) wrote his dialogues, he felt the need to directly question Aristotle as the voice of the status quo authority. The Galilean character *Simplicio*, whose name is enough of a cognate to convey the English meaning, carries Aristotle's banner.

The weight of modern science would appear to be rather cruel to Aristotle. He came up with an ultimately untenable picture of force and motion. His name is attached to a geocentric astronomical model that would literally cause suffering to future scientists (more on this intrigue later). But these are not fair ways to remember Aristotle, and to neglect the major contributions that he and his fellow Greeks left as an imprint on Western culture. Davis (2004) has an interesting way to look at human knowledge. He looks at various movements and the ideas they create as bifurcations, and through this model he builds something of a tree. At the base of the structure that produced Newton and the modern science that succeeded him, sits Aristotle's metaphysics. As Davis describes it, "the study of metaphysics, for Aristotle, had to do with the identification of unchanging laws and principles that governed forms and phenomena that exist in the realm of the physical" (2004, p. 16). Aristotle is a pillar for scientific inquiry ingrained into the very fabric of Western thought.

Understanding how this fabric weaves into individual development requires socio-cultural theory, which provides a framework for understanding intellectual development in the social settings that human beings inhabit. Some versions of the theory (Rogoff, 1990) describe mechanisms for cultural transmission (this would be like a school, but the definition is not nearly so rigid) and framing (these are the tools that structure knowledge, language is one of countless examples) of knowledge as indispensable in cognitive growth. Perhaps, in that sense, it should not be too surprising when a student spontaneously presents an Aristotelian-like worldview in a science class. Students are embedded in a Western-culture, where the Aristotelian logic process permeates the socio-cultural milieu. These students are echoing an intellectual tradition chiseled into their experiences from the nascent moments of their participation in wider Western society.

Figure 2: The Aristotelian/Ptolemaic/Christian Geocentric Universe*

II.2.2 Medieval Physics

After Aristotle, the written record on the study of force and motion seems to lull. Over a period of a thousand years, Greece falls, Rome rises (and falls), and Christians come to dominate Europe. Motion of course does not go away, but scholarly insights are not typically recorded. One interesting exception is the case of John Philoponous, a fifth century philosopher from Byzantine era Egypt. In Stinner (1994) historical review, he conveys Philoponous's view as follows:

$$V \propto F - R$$

This relationship removes Aristotle's problem of the vacuum condition. Removal of resistance no longer creates an infinite force. Again, because velocity and force are proportional, the relationship conveys force as being an internal property of a moving object. This is impetus theory, and has been shown to be alive and well in many physics classrooms (McCloskey, 1983).

Other middle age work comes much later, from Buridan and his student Oresme in France. Buridan further refined the impetus theory, defining force as follows:

$$F = mv$$

This looks suspiciously like the modern momentum formula, though as Buridan ascribed this value to force, it appears that he felt that the 'momentum' (to use the modern word for the quantity) was causing the motion. This relationship also predicts that more massive objects will fall faster than less massive ones. More mass would be predicted to have more force. In Stinner's treatment, he attributes a remarkable statement to Oresme: "it is not possible to detect uniform rectilinear motion" (p. 79). This is very nearly a statement of inertia, and leads into some of the thought experiments carried out by Galileo as he explored relativity.

II.3 The Heliocentric Universe

Nearly everyone is familiar with the story of Nicholas Copernicus, a Polish astronomer. His claim that the sun sits in the center of the universe was revolutionary. To put it in context, the modern day equivalent may be trying to convince a crowd of onlookers that the high-noon sky is orange (yet basing these assertions on tireless observation and theoretical work). The Aristotelian universe was so well ingrained into consciousness that questioning it was unfathomable.

Copernicus's theory was in response to a perplexing problem. If one tracks the objects in the nighttime sky, the stars engage in regular, predictable motion across the sky. The planets, on the other hand, sometimes have backwards, 'retrograde' motion, swimming against the tide of stars. In order to account for this, a system of epicycles was introduced, where one could predict the motion of the planets through these epicycles. If a planet has moons, then one would have nested epicycles. The solution may not seem elegant, but it does account for the movements observed in the sky.

There are no epicycles in a heliocentric model; objects maintain a constant elliptical course. The price of the Copernican position is that man is no longer at the center of the universe. A lengthy discussion on cognitive development is forthcoming, but the connection to Piaget's ideas about centration and decentration (Piaget, 1955) are too tempting to pass up. Although egocentrism is the preferred term in Piagetian literature, it is clearer under the name of 'centration'/ 'de-centration' which do less to try to usurp an English word with a negative connotation.

Young children frequently express thoughts that demonstrate that they have little awareness of a world beyond themselves. Early childhood educators will frequently note the phenomenon in a child's emotional development, but there are cognitive considerations as well. Two young children (under the age of six, for instance) will talk past each other, having the tempo and matching the others void in conversation. But the content of what they say will be unrelated. Similarly, the same children will struggle if asked to solve a problem beyond their own perspective. As with any Piagetian research, the usual caveats apply (i.e., context may change the results, either by changing the situation, or by posing the question to a child who was not raised in a Western European tradition).

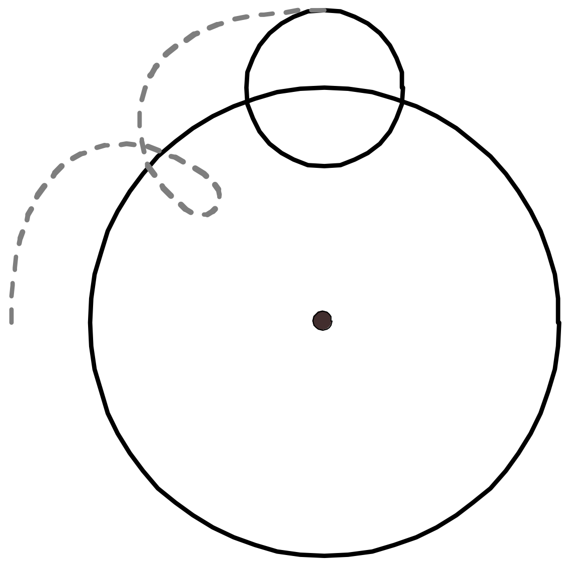


Figure 3: Epicycles. The dashed line shows the retrograde motion an observer at the center would see.

Copernicus started the process that would shed away a level of societal centration. Cognitive change in an individual is a difficult process; therefore, it is not unreasonable to suggest that the problem in society-at-large would be a disconcerting struggle (unfortunately Darwin is well out of my scope). The mythology surrounding Copernicus suggests that his book was published on the day of his death. One of the last things he got to see was the published sum of his work. Because of this, no organized backlash developed against Copernicus. He kept the church abreast of his ideas, and the local clergy seemed to regard his thinking as an interesting alternative mathematical model, a curious quirk to describe the geocentric reality. Santillana's introduction to a Galilean text sums up the reaction to Copernicus: "reality…has nothing to do with mathematical abstractions" (Galilei, 1953).

Kepler, a German astronomer and the next figure in the progression we are following, elaborated upon Copernican theory. He devised three laws to describe planetary motion, which are typically treated in a second semester of undergraduate classical mechanics. These laws are conceptually important, since they drive the understanding of the universe further from the Aristotelian model, and are directly mentioned in the *Principia* as an inspiration of sorts to Newton's thinking. Conceptually, Kepler put forward the idea that planets travel in ellipses, not circular paths, as described by Aristotle. He correctly identified the consequences of this. A planet's velocity would not be constant throughout its orbit. He also surmised that planets further away from the sun would move slower. But he could not describe a reason for the motion; one would need a law of gravitation in order to do that. During Kepler's time, there is still a missing piece to prove the Copernican hypothesis. Halley directly referenced this piece when he announced Newton's publication to his colleagues in 1688.

II.4 Galilean Physics

Galileo, a figure from the Italian Renaissance, is one of history's darlings, for good reason. His life encompasses a compelling narrative, including, at least by myth, a tour with a famous telescope, science related performance art in Pisa, and time in jail. His life symbolizes the struggles of modernity, enlightenment, and intellectualism against regressive forces. In short, writing about Galileo is an eminently enjoyable exercise. In addition to his scientific mind and personal drama, Galileo left behind a set of often witty writings, buoyed by his fictional trio of Salviati, Sagredo, and Simplicio. These three represented the authority of Aristotle (Simplicio), the radical embodiment of Copernican thought (Sagredo), and the man caught in the middle (Salviati).

Beyond support of the Copernican system and general renown for his telescope, Galileo's studies in mechanics are also noteworthy. For the purposes of this paper, what is most impressive is the progress Galileo made in considerations of velocity and acceleration, describing much of the kinematics that is taught in a high school physics course. Once again, Galileo sets this discussion as a discourse between Sagredo, Salviati, and Simplicio, and relies heavily on the use of though experiments. Much of what is mentioned here is covered in 'The Third Day' of discussions between the trio, contained within the *Dialogue Concerning the Two New World Sciences* (Galilei, 1991).

Galileo concretely defines velocity through the use of time intervals. This allows him to set the stage for a treatment of relative motion. He then defines acceleration as a continually applied impressed force, stating that "uniformly accelerated motion is such that its speed increases in proportion to the space traversed" (Galilei, 1991). However, Galileo does not quite fully realize the second law of motion, and still argues for some type of impetus. Sagredo, Galileo's own voice, claims that an object thrown upward experiences a continually diminished force ("Sagr: …Since, as it seems to me, the force [*virtù*] impressed by the agent projecting the body upwards diminishes continuously." p. 165). This is contrary to Newtonian theory, where the force remains constant as velocity decreases. Galileo also reaches certain aspects of the third law. He argues that if a stone is at rest on his hand, then there must be some force equal to that of gravity to keep the stone stationary. Otherwise, the stone would exhibit some sort of motion.

Philosophically, it can be said that Galileo cemented the role idealization in science (French, S. and Ladyman, 1998; McMullen, 1985), a stance that would echo through Newton's work and still reverberates among scientists today. Galileo was a pure empiricist, and strived to create a model of motion that Cartwright (1997) calls a 'nomological machine,' a "a fixed (enough) arrangement of components, or factors, with stable (enough) capacities that in the right sort of stable (enough) environment will, with repeated operation, give rise to the kind of regular behaviour that we describe in our scientific laws," (p. 66). Galileo's scientific process is leading him to make generalizations about the physical world, but based squarely on his observations. He is attempting to build a nomological machine that accurately describes force and motion.

In the nomological machine view, Newton simply built a better machine. His machine described the motion of the planets and falling objects in one elegant solution. Newton's approach breaks the system down, reducing the machine to component forces, and the mathematical idealization ends up being a powerful tool. In fact, the idealization ends up being so powerful that it exposes a rift in the philosophy of science, still played out by theoreticians (rationalists) and experimentalists (empiricists; Newton himself doesn't fit neatly in either theory, his work has elements of rationalism and empiricism, thus he is my favorite type of –ist, a pragmatist).

Feynman, a famous twentieth U.S. physicist, when discussing Newton's achievements, would write, "when a law is right it can be used to find another one. If we have confidence in a law, then if something appears to be wrong it can suggest to us another phenomenon," (Feynman, 1964/1995, p. 16). He is to one of the greatest achievements of Newtonian mechanics, the ability to infer the existence of invisible bodies in the solar system. In this case he is directly referring to Jupiter's moon, which can be 'seen' by looking at how Jupiter's orbit 'wobbles' versus the expected calculation of the 'ideal' system, as is, a system without any moons. The nomological machine view accuses Feynman of having it backwards. Empirical data suggests that the machine is broken, and must be revised to account for these wobbles. In the rationalist view, the physical law has primacy, and knowledge is derived from the physical law. In the empiricist view, data dictates the law.

Ideally empirical idealism can lead to rational idealism. Empirical idealism is the nomological machine. It suggests building a context simple enough where the laws can be laid bare and easily understood. Thus, physics teachers feel comfortable stripping out cogs in the nomological machines. For example, friction is ignored in motion, all collisions are perfectly elastic, and quantum probabilities can be exactly known. They are simply building an empirical nomological machine that will be revised as the context becomes increasingly complex. Yet there is vast power within the laws of physics, and the laws themselves can be used as tools to build new knowledge.

In the terms of Newtonian mechanics, the law of universal gravitation is a type of nomological machine. If one takes the stance that universal gravitation is Newton's signature achievement (as Cartwright implies), then this law flows from empirical observation. However, one can take the stance that the laws of motion are Newton's signature achievement; the laws are a monument in the annals of rationalism. But a more pragmatic take is to see that Newton needed empirical data to develop his rationalistic ideal. Once the rational ideal is in place, it becomes a ferocious weapon for creating new knowledge.

Nersessian (1999) puts this debate back into an educational context, claiming that idealization is an integral part of conceptual change. Historically, this can be seen by looking at the empirical idealization of Kepler, Galileo, and Newton and Newton's subsequent rational idealization. It is also possible to observe students struggling with idealization. Clement (1982) compared the ideas of his own students to those of Galileo's. He takes discourse recorded from the students, and then compares it to the discourse of Sagredo, and notes that there are striking similarities. The approach is appropriate, and comparing the discourses of the two groups a clever idea, even as Clement grants that his students do not have nearly the intellectual resources of Galileo. This is a tempting direction to go in, especially if the students have some training in kinematics and are having difficulty making the leap to Newtonian dynamics. Galileo's writings provide a clear picture of learning, and can be used to help understand intermediary understanding, as a student moves from their initial conception to Newtonian understanding. Galileo's writings also highlight the challenges, obstacles, and dilemmas faced in developing new understandings. However, as a general rule, it seems that very few initial student conceptions even reach the level that Galileo achieved (as has been briefly outlined earlier, and will be visited again).

A brief word should be mentioned about the Inquisition, since this is a key part of any treatment of Galileo's life. After several confrontations with the church, Galileo was jailed in 1633 and forced to recant his heliocentric beliefs. His jail sentence was commuted to house arrest, and it is at this time that he wrote the *Dialogues Concerning Two New Sciences*, which, as seen, was instrumental in the development of classical physics. After Galileo's death, the Roman Catholic Church gradually came to terms with Galileo and his ideas.

In neo-Piagetian cognitive psychology, a system of cognitive growth termed dynamic systems theory (Smith & Thelen, 2003)[3] has provided a model not only for stage-like cognitive growth, but a way to conceptualize the transitions between stages. In short, the theory attempts to explain how complex cognitive structures can arise out of simpler ones. As a result, there is not only a treatment of a stage (a stable configuration of cognitive structures) but also an impetus to change stages. When the cognitive structure becomes unstable, it will seek out a more stable configuration. Applying dynamic systems theory to the case of Galileo and the Roman Catholic Church is well beyond what the framers of the theory had in mind. The evidence for the theory is based in quantitative data, and arbitrarily applying it as a historical lens is a slight over simplification of the scope of the theory. However, Piaget and García (1989) do set the stage for the use of developmental theory as a tool for examining historical events, and as has already been mentioned, Piaget's own ideas about centration are not without their own historical parallels.

In that sense, the results of the Inquisition, rather than a condemnation of the Catholic Church, serve as an example of how difficult cognitive change can be. Galileo's trial and sentencing can be thought of as the 'instability,' as two disparate cognitive models attempt to reconcile with one another. Of course, in this sense, there is no central model; geocentrism and heliocentrism cannot co-exist. Compare this to the Piagetian task of object permanence (Piaget & Inhelder, 1966). In this task, an infant either believes, or does not believe, than an object exists after they can no longer see it. In cognitive development, there are also times when a cognitive leap must be made, and there is no turning back.

Students studying mechanics are asked to measure their beliefs and understanding of two equally disparate mental models: the one of Newton and the intuitive, more Aristotelian model they often bring into the classroom. The expectation cannot be that the transition will be easy. Nor can the expectation be that they will simply 'get' the new model because they are told so, and shown incontrovertible proof in the form of equations. Students are being asked to adopt a new model, and this model must afford them some level of cognitive stability. If not, they will not adopt the Newtonian model; regardless of their dexterity with the mathematical equations they learn.

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[3] Dynamic systems theory embeds Piaget's theory of equilibration (e.g., Smith & Thelen, 2003). In Thelen's work, she makes heavy use of Piagetian theory. Her work builds upon the qualitative base of Piaget's theory and further refines it.

II.5 Summary of the genesis of force

At this point, it makes sense to take a step back and look at the big picture of the genesis of the concept of force across Europe. The figure below superimposes a timeline on a map to give an overview of when and where the figures discussed in this paper made their contributions.

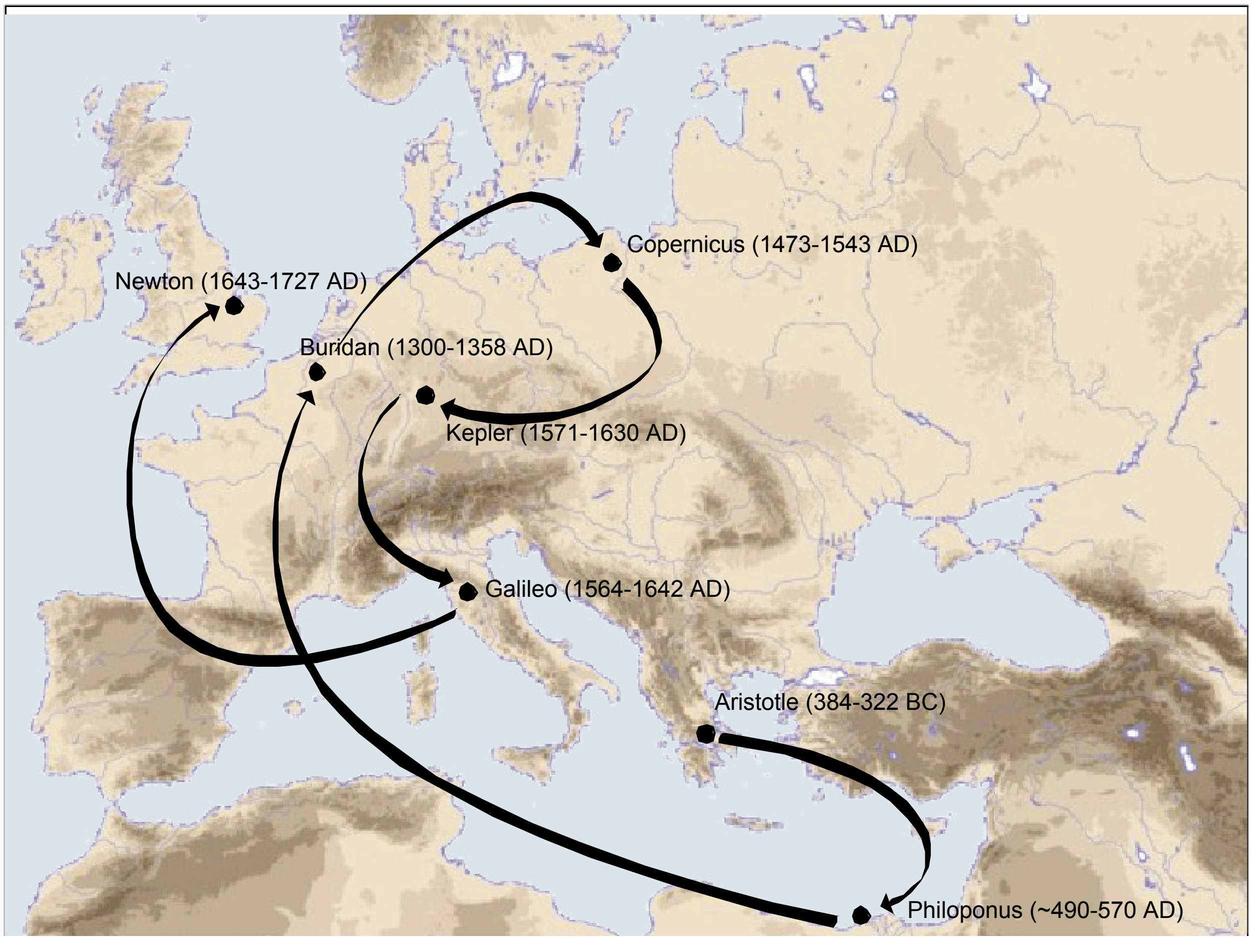

Figure 4: The genesis of the concept of force across Western Europe from Aristotle to Newton

Even more interesting is a more narrative presentation of the growth of the idea of force. The table below lists each historical figure and their contribution as the first two columns. Thus the first two columns of the table are straightforward, as each marked a major leap forward in scientific thought. However, each contribution is matched to cognitive and epistemological obstacles, mitigated by contextual considerations. The cognitive obstacles tell of the roadblocks each scientist faced, ideas that they had that would be revisited by future scientists. The contextual considerations column, for lack of a better name, discusses what factors limited the contributor. Each of these ideas was wholly correct within a given context, that is to say they make sense in a given framework. For example, in an environment where zero resistance is impossible, impetus would seem to be a complete theory.

The column labeled epistemological obstacles addresses what barriers limited the contributor's thinking. For this paper, there are two relevant categories for epistemological obstacles: centration and representational tools. Centration is the (lack) of a psychological tool[4], and covers thinking about the world in anthropocentric terms. That is, the view is internally coherent, yet would be considered insufficient with a wider lens. This could be likened to a flat earth conception: from a fixed vantage point the earth is flat, yet moving around on the surface uncovers the need for a more comprehensive theory.

Understanding that the current framework is insufficient and being able to describe a new theory are different matters. Forming the new theory often requires the creation of new representational tools (cf. Vygotsky's material tools, 1986) to frame the new thought. Once these tools are conceived they become accessible to any one to help understand the new theory. Thus, the label of tools in the table below refers to a contributor who had overcome centration, yet remained stymied in the ability to completely represent the problem to form a new understanding. Copernicus is the classic case. He had broken through the centration obstacle to discuss a heliocentric universe, but lacked the representational tools to fully explain the new model.

The centration and representational tools obstacles are a cyclical progression that relates closely to equilibrium and disequilibrium. The last column exists to encompass this, but can be extended to a wider reaction. While a theory exists unchallenged, there is equilibrium within the community. However, as a theory is questioned, the community can fall into disequilibrium as both the theory and the challenger endure greater scrutiny. This is finally resolved within the community through the genesis of new representational tools for understanding the theory, which help build (scaffold) the new understandings across a wider audience.

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[4] A psychological tool is an idea forwarded by Vygotsky (1986) that separates physical tools from mental ones. The idea presented here is not in a purist's form. Vygotsky's psychological tools refer to metal tools with transformative properties. This would include things such as language or algebraic notation. Including centration pushes Vygotsky's definition, as it is the act of decentering that has transformative properties.

Philosopher	**Contribution**	**Cognitive Obstacles**	**Contextual Considerations**	**Epistemological Obstacle**	
Aristotle	- Pioneered a logical form of thought that took hold across the Western world, - Made philosophical contributions to the nature of the universe, - Made philosophical contributions to the motion of objects.	- Could not conceive of a universe without resistance. - Viewed Earth as center of universe	On Earth, resistance is omnipresent. Possessed a worldview that precluded voyage beyond Earth.	Centration (sees universe in explicitly anthropocentric terms, e.g., geocentric earth and omnipresent friction; in general see 'Cognitive Obstacles' column)	Equilibrium
Philoponus	- First statement of impetus - Resolves problems that would arise from no resistance	- Force is internal to object	Like Aristotle, theory matches direct experiences	Centration	
Buridan	- Refines impetus theory, describing force in similar terms to momentum - Further quantifies impetus - Sows seeds of Copernican revolution	- Still describes force as internal to object - Sees force as proportional to mass (heavy objects fall faster)	Theory matches experience	Centration	
Copernicus	- Breaks geocentric model, creates a heliocentric universe - Reasons using careful observations, beginning a framework for scientific Renaissance	- Sees orbits as perfectly circular - No framework for describing mechanism for orbits	Running completely counter to the previous theory, this is a monumental first step	Lacks effective tools to completely describe and unify theory (henceforth labeled as Representational Tools)	Disequilibrium
Kepler	- Described elliptical orbital paths of	- No framework to describe a mechanism for	Framework did not exist, observations cause framework,	Representational Tools	

	planetary orbits - Understood the quantitative ramifications of elliptical orbits	orbits	not reverse		
Galileo	- Developed extraordinary experimental framework - Documented uniform acceleration - Keen observation of the planets - Early proponent of a Copernican universe	No mathematical framework for understanding motion. Could not completely separate from impetus.	Pushed Aristotelian motion to the tipping point without causing a complete revolution.	Representational Tools (specifically lacks rigorous quantitative definitions for seeing through theory)	
Newton	- 'Discovered' gravity - Invented calculus - Developed a rigorous mathematical framework for understanding motion - Explained the motion of the planets and the fall of a rock in one elegant theory - Contributed greatly to the study of optics	Considered time invariant	Time is very close to invariant until relative motion becomes much faster than anything Newton experienced.	Centration	Equilibrium

Table 1: Genesis and considerations in the development of force

One of the interesting ramifications of this table is the role that centration and representational tool use play in the development of force. The general pattern that seems to arise is that a new theory is described, and is then fleshed out with representational tools leading not only to a fuller understanding of the model, but also to mechanisms for others to learn and build upon the new theory. Advances in the model are synthesized with related fields, eventually leading to disequilibrium. The only way to restore equilibrium is with a completely new model, which is developed along with accordingly relevant representational tools. In hindsight, it is possible to say that the shortcomings of a prior model are relics of anthropocentric thought, and resemble what cognitive science labels as centration. We can play with the words a bit and label this is anthropocentration, which again only happens with the benefit of hindsight. Future learners have to overcome the same cognitive obstacles. However, with the theory and representational tools in place for considering more modern scientific ideas, students can perhaps experience their own scientific revolution on a timescale on the order of several years, rather than millennia.

Specifically, there are two major points of drastic epistemological change in the historical genesis of force. Copernicus presented a new model, breaking with the scientific tradition that had persevered since antiquity. This is the first major mark of epistemological change, and one of decentration ushering in disequilibrium. Copernican heliocentrism proposes an elegant answer to the puzzle presented by epicycles, but introduces many new questions. The aesthetic appeal of the heliocentric model does not describe why planets would orbit the sun rather than the Earth. The subsequent scientists could explore these questions, but a succinct answer seemed hopeless. Newton's contribution is remarkable. The second major epistemological change is his development of a new set of representational tools that describe gravity and provide a framework for understanding the dynamics of motion. These tools quantify the Copernican heliocentric hypothesis to such an extreme degree that the validity of the hypothesis is an apparent consequence of Newtonian theory. Further, once published, these tools are not private or unique to Newton. Once published, anyone can arrive at Newton's conclusions. The revolution that spanned millennia can happen privately within years.

II.6 The Consequences of Newtonian Physics

When I first started working on this paper, I was driven by a question. Newton was able to see through 1500 years of written history and rewrite the science of mechanics. The intellectual feat was so magnificent that it provides a universally accepted high point in the scientific Renaissance. Even Newton's contemporaries immediately recognized the significance of his progress. Yet Newton was humble and deferential; he is famously quoted as saying "if I have seen farther, it is because I have stood on the shoulders of giants." So my questions were these: if Newton relied on a series of giants, who exactly were they? If this reliance spurred on the creation of a new physics, then, if paired with a clever pedagogy, could these giants also aid in the instruction of students and their Aristotelian or medieval conceptions about motion?

The blunt answer to my questions is no, for several reasons. Though it is clear from a reading of the *Principia* (Newton, 1995) that Newton was well aware of the progress of his predecessors, his insights are clearly the work of his own creative mind. To borrow from cognitive science once again, Feldman (1994) provides a strict operational definition for the concept of creativity. The creative mind builds completely new understanding, radically changing the possibilities within a specific domain of human thought. Under this definition of creativity, Newton has few peers (emphasized by Gleick's (2003)] assertion that Newton was isolated in his intellectual endeavors). If this is the standard we set out for in science education, a plateau attainable to only the most rare of all geniuses, then the only possible outcome is disappointment.

Gruber (1981) provides a less strong conclusion that Feldman's (1994) in his analysis of the growth of Darwin's ideas. Gruber's work itself is remarkable, as he traces the origins of Darwin's thinking in the context of its time, and then tracing the genesis of the idea for natural selection through Darwin's scientific notebooks. A useful thesis to tease out of these ideas is that cognitive growth occurs only when the correct context presents itself. It would be foolish to engage in the silliness of rating geniuses; we cannot say that Newton is greater than Aristotle, nor can we say Einstein is greater than Newton. They existed in different contexts, and used the representational tools of their time to enhance the boundaries of understanding. While Einstein uncovered phenomena that unraveled with equal validity in Aristotle's time, only with generations of thought and the appropriate representational tools (in terms of strength) for framing the problem could a universe with general relativity be comprehended.

Aristotle, Galileo, Newton, and Einstein are emphatically not the students arriving in science education classes. Yet the idea that context and tools can frame their thoughts is an important point that has relevance for students, and it has not been lost on researchers (diSessa, 1988; Hammer, 2000; Hammer & Elby, 2003; Kohl & Finkelstein, 2006). The classical Vygotskian (1978) hypothesis is that language structures advanced thought. When language is subsumed as another tool in the intellectual arsenal, each scientific advance paves the path to a new, and slightly more sophisticated understanding. Students, on the other hand, still get to make use of these new tools as a mechanism for recreating the steps of others, and in the best of scenarios, contributing to advances themselves.

Although the ideas of educating people to think like Newton by digging through Newton's thoughts turns out to be impractical, there are still a variety of lessons to take away. First, in mechanics, there is a close parallel between the ideas of an individual student and the struggles that pervade conceptual education. This is reinforced even by post-Newtonian physics. Newton wrote about the absoluteness of time, an idea that would be overturned in the subsequent revolution of physics. Biases that one takes from everyday observation of the physical world can clearly be deeply ingrained, and these conceptions can be inflexible even in the face of scientific evidence.

Beyond educational concerns, it is also possible to tie the ideas behind human development to scientific growth. This at least suggests a superficial connection between development and the growth of new scientific ideas. In the minds of the vast majority of physics students, the events of the scientific revolution are being recreated on a miniature timescale. Children are adopting the ideas of motion ascribed to Aristotle and the medieval scientists. Even geocentrism lives on in a conceptual form in the minds of young thinkers (Vosniadou & Brewer, 1992), though in a strange form as children balance their own observations with the conflicting socially gathered evidence for a round earth and heliocentric solar system.

The connection between human development and mechanics brings about a final, though unintentional, point. Newtonian mechanics is no longer considered to be an accurate description of the physical world. Nails were set into its coffin with the rise of Einstein's theory of relativity, quantum mechanics, and the general demise of a deterministic, clockwork universe. That does not mean that Newtonian mechanics are without use, since they still provide accurate approximations of human-scale phenomena, and the mathematical methods developed as Newtonian mechanics still play a central role in the study of physics. But utility to engineers and sound mathematics do not develop a convincing case that classical mechanics should be the center point of an introduction to physics.

The primacy of classical mechanics arises in part from the magnitude of the accomplishment achieved. It provided a roadmap for abstracting the physical world, and provided an incredibly rich and complex system for conceptualizing the world around us. Newtonian mechanics, and the individual, mini-scientific revolution that each individual undergoes in learning this content open up new doors in cognitive thought. This is not to suggest that there are not other avenues to realize the same possibilities. But the Newtonian revolution is archetypal, and reoccurs in most every individual. It is an excellent starting point for a discussion on science education more generally.

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[*] (Van Helden, 1995)

Part III: The Role of Cognitive Science

One of the most striking aspects in the growth of scientific thinking is how scientific thought can be systematized into a group of consistent obstacles. In the discussion on the growth of dynamics put forth in the previous section, centration and representational tool use were central epistemological obstacles. Cognitive science provides a mechanism for framing these obstacles in a more rigorous manner. One of the most fascinating aspects of human thought is the fact that it can grow and adapt. Cognitive science is an exploration into the learning mind. There is an entire science devoted to the growth of knowledge: epistemology. From the previous historical discussion, one way to frame the pursuit of science is an ever-increasing base of knowledge concerning observable phenomena. This makes epistemology a meta-science, knowledge of knowledge.

Cognitive psychology has been treated with degrees of increasing sophistication. This discussion starts with Jean Piaget, a biologist turned epistemologist who provided a robust theory for individual intellectual growth. Piaget's work spans nearly five decades, and still serves as a reliable starting point in an inquiry in cognitive development. As a testament to how powerful his work is, modern studies continuing in his direction are called neo-Piagetians. Piaget's ideas are also directly applicable to the growth of capacity for scientific thought. Piaget developed a stage theory, with divisions in stages marked by sharp changes in the capacity for cognitive thought. In his explanation of the final stage, formal operational thinking, he specifically notes an ability to understand Newtonian mechanics as one of the hallmarks of the stage.

The capacity to understand does not automatically connote understanding. Previously, the exploits of Aristotle, Galileo, Newton, and others were presented, some of the finest thinkers in science history. If cognitive development is considered on a spectrum, with the outer region reserved for the finest thinkers in all of history, there is no doubt where this triumvirate would lie; their intellect is unchallenged, and for the most part, unmatched. Despite the intense combined intellectual effort brought to bear on the topic, classical mechanics was elusive for a millennium.

As a result, we do not expect a spontaneous understanding of intricate scientific content to be the norm. This paints a clear role for education, which is a social enterprise as one individual or a collection of individuals attempts to pass down knowledge to another set of individuals. Education itself is a science, resting upon ideas of socio-cultural cognitive development. Studies in education and science education are the topic of the third part of this paper, but the cognitive ideas that underlie them are discussed here. While modern theories of socio-cultural cognitive development can be tracked to Vygotsky (whose literature actually predates Piaget's), there has been much development in the last 15 years with repercussions for science education.

The section is structured in a way to give appropriate weight to the major contributions of Jean Piaget and Lev Vygotsky, as compare the seemingly nonreconciliatory theories[5]. However, in the intervening years, a number of hybrid ideas have emerged that make use of various aspects of both contributions. These theories are considered classical, and an effort will be made to consider more modern theories; the theories have been expanded, and in some cases hybridized.

III.1 Constructivism & Stage Theory

Constructivism and stage theory are two hallmarks of Jean Piaget's theory of cognitive development. Constructivism has grown into a philosophical movement (e.g., Davis, 2004; Glasersfeld, 1991; Jonassen, 1991) beyond cognitive and intellectual development. The movement is a statement that the individual constructs an understanding (or even reality) by mediating internal ideas with external representations. In practice, this connotes that learning is driven by an active engagement with one's surroundings. Constructivism as a theory is used frequently in early childhood (3-5 years old) classrooms (e.g., Kamii & DeVries, 1978) and it's influences can be seen in reform minded science (and other content) education efforts all the way through undergraduate levels (Laws, 1991 Workshop Physics is labeled as 'learning physics by doing it').

The second major element of Piaget's theory, stage theory, asserts that children go through a sequence of four specific stages. Stages cannot be skipped, and must happen in order. There is no backward movement among the stages. This work is not without critics; however, stage theory has been recently supported with more sophisticated analyses (Jansen & Van der Maas, 2001; Smith & Thelen, 2003). In science education, researchers have argued for stage-like progression though various content. This is an extension of Piaget's ideas, and as seen, can find parallels in historical study. Both constructivism and stage theory have major implications for science education and will be explored in greater detail.

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[5] This, unfortunately, is a rather provocative statement. Certain researchers (e.g., Cobb, Wood, & Yackel, 1990; Hatano, 2002) have contended that it is possible to reconcile the two theories. Feldman [year], has laid out the more purist position that as Piaget and Vygotsky originally stated the theories, they are incompatible. This does not prevent future permutations from reconciling, as Cole or Hatano's reinterpretations do. However, in looking at the specifics of Piaget and Vygotsky's claims, including Piaget's (Vygotsky, 1986) direct address of Vygotsky's ideas, where he superficially acquiesces several points, Feldman more than builds his case.

III.1.1 Constructivism

According to Piaget, a child employs three major processes in their construction of understanding: assimilation, accommodation and equilibration. Piaget is often formal in how he frames his ideas, giving his thoughts a quantitative flavor. In the case of assimilation, Piaget records the steps below:

> $a + x \rightarrow b$
> $b + y \rightarrow c$
> $c + z \rightarrow a$, etc.
> (Piaget, 1952, p. 5)

The set {a, b, c} represent the 'organized totality' (i.e., the child) while the set {x, y, z} are stimuli from the outside environment. One way to make this formulation more tangible is via analogy. Chemical interactions are a satisfactory, yet not perfect vehicle for analogy. Chemical A is a complex substance combined with chemical X, leading to a reaction producing chemical B. However, rather than chemicals, Piaget is considering elements of a child's cognition, under transformation from interactions with exterior influences. While the child interacts with the outside environment (chemical x), he uses internal mechanisms (a) to come to a new understanding (b).

The analogy leaves out several important aspects. The chemical reaction is passive, it happens only in the right conditions. This is not the case with assimilation. These happen continuously, there is no volition or proper conditions for assimilation. Further, the stimulus that initiates the process need not be internal. Two internal cognitive processes can interact to lead to assimilation.

Piaget also provides a more qualitative description of assimilation, in a description of an infant's tendency to exhibit repetitive behavior:

> In studying the use of reflexes we have ascertained the existence of a fundamental tendency whose manifestations we shall rediscover at each new stage of intellectual development: the tendency toward repetition of behavior patterns and toward the utilization of external objects in the framework of such repetition. This assimilation—simultaneously reproductive, generalizing, and recognitory—constitutes the basis of functional use [of the studied behavior]. Assimilation is therefore indispensable to [reflex] accommodation. Moreover, it is the dynamic expression of the static fact of organization. From this double point of view it emerges as a basic fact, the psychological analysis of which must yield genetic conclusions. (Piaget, 1952, p. 42)

While in the above quote Piaget is discussing the behaviors of infants, he makes use of assimilation across all of development. The process does not disappear as the child leaves infancy, rather, it is a mechanism that drives development in subsequent stages as well. Piaget also alludes to the process of accommodation, a tandem and inseparable process with assimilation.

In Piaget's words, "adaptation is an equilibrium between assimilation and accommodation" (Piaget, 1952, p. 6). Accommodation, like assimilation is defined formally through a mathematical analogy:

$a + x' \rightarrow b'$
$b' + y \rightarrow c$
$c + z \rightarrow a$, etc.

The assimilation sets {a, b, c} and {x, y, z} are now replaced with {a, b', c} and {x', y, z}. The simple change, x', represents a stimulus (either internal or external) exerting some change on the 'organized totality' (which is still just a child). This leads to the new psychological representation b', to which the 'organized totality' must now adapt if it will reach 'c.' Assimilation and accommodation are interactive processes. They describe a child interacting with the environment, and a resultant dynamic, constructed understanding. (Note that Posner, Strike, Hewson, & Gertzog, 1982, use a definition of assimilation and accommodation that is often cited in science education literature, but differs from Piaget's use of these words. I use Piaget's definitions.)

The easiest way to see how assimilation and accommodation work in practice and understand their relevance is to borrow an example from science education. In the late 1970s and early 1980s, researchers began to notice that students were not developing a strong qualitative understanding of undergraduate level physics (Trowbridge & McDermott, 1980; Viennot, 1979). Students had an understanding in place, along the lines of medieval physics. In the physical world they observed, objects did slow down on their own accord, and external forces were necessary to maintain constant motion, antithetical to the ideas proposed by Newton and only resolved when explicitly accounting for friction. Students assimilate the information they gather, both from the outside world and their educators into their cognitive frameworks. This very process causes a change to the change to the learner's understanding, which must be accommodated. At some point, the learner finds equilibrium between the assimilation and accommodation, which rather than being along Newtonian lines, represents an alternative and ultimately outdated framework for physics.

The student's accommodation is liked with tandem assimilation. As an explanatory model for motion is developed, future stimuli will either help reinforce the existing model, or challenge the existing beliefs. This challenge may come from a classroom; a teacher, or any other authority figure, may provide some set of information that needs to be assimilated in some manner. Harris and Koenig (2006) label this authoritative information as testimony, and have demonstrated that children from a young age will trust information received from an expert. In practice, they point to Vosniadou and Brewer (1992), who discuss mental models of the earth. In Vosniadou and Brewer's research, children clearly believe the earth is round, but do not synthesize 'testimonial' information in a traditional manner. Thus, in an attempt to assimilate this information, while still accommodating for first hand experiences, children's representations of a round Earth resemble objects like snow globes or compact discs. As an aside, this is another reminder of the danger of labeling non-traditional scientific conceptions as 'wrong.' While a snow globe hypothesis does not match accepted theory, that or similar hypotheses, are arrived at using cognitive mechanisms that should be encouraged.

High school students learning physics can be paralleled with the children coping with the shape of the earth. Traditional instruction is an idea that peppers the literature. It is often defined as a lack of research-based reform efforts (Crouch & Mazur, 2001; Hake, 1998; Redish, Saul, & Steinberg, 1997), with authors often agreeing on several salient points. Traditional instruction is lecture driven and non-interactive; this is to say that the educator employs the sponge-like epistemological stance. Knowledge is presented, and the student is to absorb it. In Piagetian theory, we already expect traditional instruction to fail. Students will assimilate the new information, but in tandem with accommodation for previous experiences. The resultant models will be based on reasonable cognitive processes, but will often not match accepted scientific theory. In practice, the same researchers constantly report on the failure of traditional instruction and outline a set of alternative models that it produces. The sponge-like epistemological stance asserts that assimilation can happen in a vacuum, yet this is impossible. The alternative is an awareness of the student's prior experiences, and an acknowledgement of the active processes of both assimilation and accommodation.

Being able to describe student ideas of scientific phenomena, both those in line with scientific thinking and any alternatives, is clearly an important aspect of teaching. The point of equilibrium between assimilation and accommodation, where the learner has developed a stable explanatory framework for physical phenomena is referred to as a conception. Piaget had room in his theory for conceptual schemas, but understood a certain dichotomy. On one hand, any one must be able to represent their conceptual knowledge. Piaget wrote, "since conceptual schemas are related to the system of organized verbal signs, progress in conceptual representation will go hand in hand with that of language" (Piaget, 1951, p. 221). Piaget also understood that these representations could be a-linguistic (Piaget, 1929). It is easy to see that everything ranging from mathematic formalism, crude drawings, to a clearly plotted graph carry some meaning that goes beyond a very strict definition of language. From a purely pragmatic point of view, this demands an assessment technique that looks at intellectual knowledge and growth not tied strictly to language.

III.1.2 Conceptions

Conceptions, scientific or otherwise, are the focal point of science education research. They are the bookkeepers of a learner's scientific growth, providing a unit to measure scientific growth the same way a meter measures displacement. Scientific conceptions can be differentiated from alternative, 'non-scientific' ones. Scientific conceptions refer to a conceptual framework that matches with accepted theory. Newtonian theory is a 'scientific' conceptual framework. An alternative, non-scientific framework does not match up with accepted theory, and is ultimately incoherent as a theoretical framework. Nowadays, Aristotelian theory is 'non-scientific.' Thus the distinction between scientific and non-scientific is community and context driven. Non-scientific conceptual frameworks can be underpinned by very scientific, systematic thought, making the convention regrettably misleading.

The nature of conceptions is still open for debate. To resolve these questions, and clarify what precisely conceptions are, I wish to step back and examine their place in a larger cognitive ecology. In Piaget's theory, cognitive development is a global process (Feldman, 1994; Vosniadou & Ioannides, 1998). In a global development model, conceptions would be symptomatic of the overall development. As the child grew cognitively, conceptions would spontaneously change with the psychological structures of the mind. Feldman's (1994) work limits development by describing changes on a spectrum from unique to universal. Universal development describes development of every single human being (perhaps the Piagetian task of object permanence, where an infant learns that an object still exists even if it is no longer physically visible), while unique development describes individual accomplishment outside the scope of all other humans. Newton's personal developments in mechanics are an example, and illustrate how singular development on a personal level can become adopted by a wider subculture (in this case, physicists). Taking Feldman's stance has implications for education. Education is an effort to transmit knowledge that a certain culture or subculture has deemed important. The type of knowledge that education is interested in is not universal, while certain knowledge or conceptions may have requisites in universal development.

The universal-unique spectrum only begins to answer questions of the nature of conceptions. While an individual conception is unique, it draws from resources across Feldman's developmental spectrum. A slight modification of this theory leads to a domain specific theory of mind, where conceptions would be bounded by cognitive context (see Fodor, 1983). Perhaps more palatable is Karmiloff-Smith's (1992) hybrid approach, which introduces what she calls 'phase' theory. While Piaget describes specific stages for development, which a child moves through more or less universally across all domains, she proposes that the domains are loosely tied together. Development in one domain can, but does not necessarily, drive understanding across different domains.

From the idea of domains it is possible to start to consider conceptions as smaller structures within a domain. Domains are related groups of related information. Conceptions have explanatory power, describing how phenomena encompassed by the domain unfurl. This builds up conceptions as miniature 'scientific' theories; in the sense that they are employed by the mind in the same manner a practicing scientist would make use of theory. This view of conceptions is called theory-theory, and has roots in Karmiloff-Smith and Inhelder's (1974) research noting that children spontaneously generated theory while working through a pan-balance task (being asked to balance an object, sometimes not weighted symmetrically). Subjects would develop a rule to try to balance at the center, a generalization that would generally help them work through the task. If the weight distribution were not symmetric (a condition which was sometimes hidden from the subject), their progress would actually be slowed down, despite the fact that the subject was showing the desirable outcome of abstracting a rule. The researchers called this a 'theory-in-action,' since the child spontaneously developed and operationalized a theory. The child had instant feedback on the efficacy of their theory and any shortcomings (i.e., failure of the symmetric rule) would quickly become apparent through experimentation, allowing for a refinement of the theory[6].

Vergnaud (1979) builds upon this with the idea of theorems-in-action. A theorem-in-action, simply, is a very limited theory, which is held true by the actor, applicable only directly in the situation at hand. Vergnaud's work is in mathematics education, but there are implications for science education, as he even spells out the similar idea of a concept-in-action. These small bits of knowledge are constantly generated and revised, as the learner delves into a given problem and actively constructs a deeper understanding.

The implication for science education is significant. The theory is a major unit of scientific thought: it represents a coherent structure capable of making predictions of the physical world. The unit of the theory can be correlated to development, and several researchers have been willing to make the jump to conceptual thought (e.g., Carey, 1986; Scholl & Leslie, 1999). A fair question to ask, however, is whether these student theories rise to the same rigorous level as scientific theories.

Scientific theories are internally consistent. In the example of Newtonian mechanics, the same laws that describe linear motion also describe rotational motion. In a wholesale application of theory-theory, a student theory on linear motion ought to apply to rotational motion. DiSessa (1993) posed this exact question, and found that students were not using a coherent theory between rotational and linear

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[6] An interesting aside to this discussion is that the authors also found that the youngest children clearly used propriocentric [i.e. feedback from their bodies] in developing ideas about how to complete the balance task. The implication is that scientific ideas can be developed from the senses, in a ground-up sort of way.

motion, despite the fact that the two tasks seem to be intimately related. There are a couple possible divergent directions. One could argue that the two types of motion are different domains, though they merge with a sufficient understanding (though It is not clear to me that anyone has ever endorsed the idea of fungible domains). DiSessa thinks that this is evidence for what he calls phenomenological primitives ('p-prims'). These are along the lines of atomic bits of scientific thought, and are free to rearrange themselves into stable configurations depending on situational context.

The p-prim model limits the ability to think of non-scientific ideas as straightforward conceptual frameworks, which has led to criticism of the idea (e.g., Chi & Slotta, 1993; Vosniadou, 2002). However, in addition to the evidence provided by diSessa, the fact that Hammer (1994) has been able to operationalize the idea and bring it into high school classrooms (1995) provide more weight to the model.

Throughout the last decade, the discussion of student conceptions and what factors lead to conceptual change has been a topic of enormous interest, and it is possible to carry on at length. The goal here is to illustrate how powerful the idea of scientific conception and conceptual change can be in science education, especially when carrying forward a set of caveats that focus on the breadth of a student's conception. By looking back at the influence of Piaget, his developmental processes and his ideas of conceptual schema, it is possible to better understand the roots of why learners hold conceptions, and better apply them in an educational setting.

Before stepping completely away from constructivism, it makes sense to look at one last outer limit of the idea. There have been radical formulations of constructivism, where the student is expected to completely construct an understanding through a manipulation and operation of the physical world.

> Radical constructivism is uninhibitedly instrumentalist. It replaces the notion of 'truth' (as true representation of an independent reality) with the notion of 'viability' within the subjects' experimental world. Consequently it refuses all metaphysical commitments and claims to be no more than one plausible model of thinking about the only world we can come to know, the world we construct as living subjects. (Glasersfeld, 1991, p. 22)

Papert (1980) labeled his radical flavor of Piaget's theory constructionism. A reasonable fear of allowing students to create their own representation is that frequently they will build the wrong representation, as seen frequently in the case of physics. To address this, Papert advocates for microworlds, computer-based environments built to encourage exploration of a narrow topic, while allowing for experimentation and exploration of a specific set of variables. Papert built Logo to teach ideas about computer programming, and diSessa (1982) and Dede et al. (1996) have built physics-based microworlds (though the Dede environment has not been tested with any community-adopted measure for conceptual learning; it appears to be an exercise in virtual reality environment building rather than an educational one with conceptual change as a primary goal).

Radical constructivists also have a disdain for school, a stance likely arising from what Piaget termed "the American problem" (Hall, 1970). American educators viewed Piaget's theory as a roadmap for speeding up the development of their children, and for giving them a sort of competitive advantage. Piaget did not see his theory in those terms at all, and felt that development occurs at it's own pace. This develops something of a paradox for educators, concisely summed up in the title of a Duckworth article "Either we're too early and they can't learn it or we're too late and they know it already" (1979). Duckworth concludes that the best educational experience enriches a child's experience, giving them depth on the level that they can approach the topic. This practice still lives on, in the form of 'differentiated' instruction, where a child can engage material on a personally meaningful level. The very notion that children see the world in different ways depending on some location in a developmental spectrum suggests the need to be able to differentiate these children. Once again, Piaget provides initial guidance with his stage theory.

III.1.3 Stage Theory and Dynamic Systems

While the roles of assimilation and accommodation have been explored in creating a constructive theory of epistemology, a third leg of the theory, equilibration, must be explored. In Piaget's studies, development could find itself in a stable position, a developmental stage. Piaget described four stable stages (Piaget & Inhelder, 1966), but assimilation and accommodation are not sufficient in describing stage change. The stages are stable cognitive configurations, and would therefore not be prone to change on their own accord.

As the child constantly acquires new information, actively constructing understanding through assimilation and accommodation, the cognitive structure of the stage can fall into disequilibrium. Disequilibrium is not stable, and therefore there is pressure on the child to change cognitive structures in order to achieve equilibrium. The 'organized totality' that is the child's mind becomes disorganized. Yet when structure is restored, the resulting understanding is richer. Equilibration to disequilibration and then back to equilibration is a constant cycle.

The ever-repetitive cycle suggests all of the most esoteric, grand, and bizarre theories of the universe have roots in the simplest levels of human experience. Piaget labeled this as the sensory-motor stage, which describes the actions of infants in an ordered way. This is a ground up model of development (Thelen, 2000), suggesting that even the basest forms of intelligence are not too mundane in forming a theoretical basis for science education.

The best mechanism for this discussion, as well as a segue for modern evidence of stage theory, is the dynamic systems explanation of the A not B error (Smith, Thelen, Titzer, & McLin, 1999; Thelen, Schöner, Scheier, & Smith, 2001). The A not B error has a rich history in psychology, as outlined in the Thelen et al. paper, but the main concern is simply understanding the nature of the task, and how it can be expanded into a useful construct for science education.

In the sensory-motor stage, children do not initially possess object permanence, a skill that allows one to perceive an object's existence, even after it has passed from immediate sensory perception. The test of this would be to hide an attractive object, a toy for instance, behind a screen. After the object has vanished, the child no longer reaches for it. The infant achieves object permanence, and if the toy is hidden behind a target, the infant will continue to reach for it. However, if two targets are presented, A and B, the infant will reach randomly, even after watching the toy be hidden behind one of the specific targets. Subsequently, the infant reaches for the target that the toy is hidden behind; however, if the experimenter changes the goal target, with the child watching, the child does not adapt, and still reaches for the original target. This specifically, is the A not B action. Finally, the child constructs an understanding that allows for the correct reaching behavior. The A not B progression, therefore, is reduced to:

No object permanence	Infant believes that object no longer exists when hidden behind target.
Random reaching	Infant reaches randomly for object when clearly hidden behind one of two targets
A not B error	Infant continually reaches for same target when object is hidden between one of two targets, even if hiding spot has changed
Correct reaching	Infant consistently reaches for the correct target

Dynamic systems theory is a modern approach to Piaget's ideas, and Thelen et al. describe the A not B task in the language of the new theory, which in turn provides a new dimension to the equilibration process. The researchers write, "the starting point of the dynamic model is with new assumptions. The A-not-B error is not about what infants have and do not have as enduring concepts, traits, or deficits, but what they are doing and have done" (Thelen et al., 2001). This postulate demands looking at epistemology not as cognitive or psychological deficits, but much like constructivism suggests, knowledge as a continually growing sum of previous experiences.

With the strict retrospective postulate, dynamic systems theorists can build a mathematical relationship that predicts both the stability and changes in the infant reaching behavior. The exact formulation of the expression is omitted, as the role of a mathematical expression in a vacuum is questionable. However, the factors that contribute to such an expression are interesting. This is expressed in the table below, with ψ used as a representation for the decision field. In each case, the factor of interest is $\tau\dot{\psi}$, the change in the decision field over time scale τ.

Factor	**Description**	**Mathematical representation**
Dynamics	A statement that the behavior is dependent on previous behavior. Likened to suddenly moving a saltshaker. One will still look in the original location as a matter of habit.	$\tau\dot{\psi} \propto -\psi$
Task input	A common sense statement that the behavior is dictated by the task being performed. The actual structure of the task can be quite complicated, as can the mathematical representation of the structure. After the task is completed once, part of the task input is the memory of previously completing the task.	$\tau\dot{\psi} \propto S$
Cooperativity	Cooperativity refers to the idea that in the face of multiple inputs, one must inhibit the other. If dynamic systems theory extends to scientific conceptions, this would state that a Newtonian conception being activated would likewise inhibit an Aristotelian one. At the same time, related conceptions could serve to cooperate and help activate similar conceptions.	$\tau\dot{\psi} \propto g$

Table 2: Factors in Dynamic Systems Theory

In simulations, with terms more carefully defined than presented here (precise forms for S and g), this leads to a recreation of the A not B error. An activation threshold is defined for each stimulus, and when the field reaches that point, the infant reaches for one of the targets. So in saying that the simulations accurately recreated A not B, the researchers are claiming that reaching thresholds were achieved in a sequence that matches the outcomes in the laboratory.

The model accurately describes a stage theory. Stages are stable, but separated by periods of disequilibrium. However, the dynamic systems brand of stage theory can accurately be moved to conceptual learning if the same processes are at play. A key element of Piaget's theory is that all higher order understanding is built from the sensory motor stages. This provides a hint that the cognitive processes that generate knowledge in infancy remain active in later stages of cognitive growth. Piaget himself described a process of conceptual learning in later stages, as children developed protoconcepts and then conceptual schemas (Piaget, 1951).

While the infant is displaying the A not B error, there is a connection to diSessa's (1988) p-prim model, or Vosniadou and Brewer's (1992) account of the models of the earth. Like the infant who will reach randomly for one of the two stimuli, the student will apply different conceptual frameworks, sometimes changing applied without an apparent reason. The targets A or B take on the role of concepts that can be applied to a given scientific problem. In this case, we expect that student concepts activate, much like infant reaching, based on system dynamics, the task input, and cooperativity.

Applying dynamic systems to student concepts is not an accepted epistemological theory. There is no experimental backing for this proposition. Hammer and Brown (in press) have also suggested that student learning has the fingerprints of a dynamic system, but turn to diSessa's p-prim model rather than fully embracing the completely ground up approach presented previously. In contrast to the highly refined infant research, applying dynamic systems to student conception lacks the body of empirical work and the ensuing quantitative definition.

However, successful future study would have clear benefits. It would reinforce the idea that conceptions are built through experiences that begin at infancy, pointing to the fact that successful science education begins at a very young age. The theory would also suggest that conceptual change rests upon what current conceptions are held. In the language of the theory, the task input must be crafted in such a way that it resonates with the current system dynamics, as in a dynamic system it is possible to both induce and inhibit change. Finally, the theory provides an excellent quantitative measuring stick in the quest to measure units of conceptions. Learning can be seen as the change of the conceptual field versus a controlled environment.

III.2 Cultural considerations in cognitive development

The last stage in Piagetian development is called formal operations. It implies an ability to reason abstractly, that is to say an individual can perform a cognitive operation from multiple (sometimes said as all) vantage points. In essence, centration is no longer a primary, personal cognitive obstacle (although the 'anthropocentration' defined in Part I can still be in play). In the realm of science, Piaget claimed that a student, upon reaching this final stage, would be able to make sense of Newtonian mechanics (Piaget, 1970). However, the science education literature makes it clear that this does not happen on its own. Instead, rather than displaying Newtonian conceptions, students possess a hodgepodge of conceptions with roots in historical development. The strongest possible interpretation is that development gives the potential for knowledge, but does nothing to confer such knowledge.

This is the basis for splitting epistemology and learning. Epistemology is a meta-level of learning, describing what mechanisms govern learning, but not giving a cookbook-like formulation of how to teach someone content (classical mechanics, for example). A simple example can be drawn from the historical section. Galileo undoubtedly possessed formal operations, yet failed to formulate classical mechanics. There is more at play in learning than just development.

Feldman's (1994) universal to unique spectrum has utility in this discussion. Feldman's position is that Piaget's theory of epistemology describes universal development, a shared set of experiences that in part defines humanity (or at least the psychological aspects of humanity). On the other side of the spectrum is unique development. This refers to the learning and studies that an individual undertakes. Knowledge can be shared universally, culturally, or be domain specific; however, unique knowledge is created on a personal level, as are the mechanisms to share and spread the new knowledge. New ideas flow out of the unique end of the spectrum, and can be compared to Newton's innovations in thinking about gravity and dynamics. These ideas were quickly adopted by other scientists within his domain, and have spread to many other domains as well. The important consideration is that universal and unique development are not linked. Universal development does not predict how one will come to learn new knowledge in more narrowly defined domain specific areas of the spectrum.

In practice, this limits the utility of a development-only approach to education, which would focus on enhancing universal processes. This introduces potential limitation of Piagetian style theory. Piaget's theory has been criticized in that it does not adequately predict development across different cultures (e.g. Göncü, Mistry, & Mosier, 2000 discuss cross-cultural infant play with a decidedly non-Piagetian bent). The whole picture is more complicated; for example, Dasen (1972) discusses the cross-cultural successes of qualitative elements of Piaget's research. What should be a binary choice between an ubiquitous developmental theory or the need for cultural-specific epistemological theories is not a clear-cut dichotomy. However, even one counter example to the more monolithic styled Piagetian theory is enough to consider enriching the theory through the addition of a cultural perspective. Researchers have demonstrated that there is a cultural context to development. More to the point, educators cannot expect a homogenous group of children in a modern classroom. If cultures do not share epistemologies, there must be a deep understanding of how cultural differences can lead to differences in learning.

A culture also defines a shared set of tools. One of the striking aspects of historical development of force and motion, as seen in the previous section of this paper, was that innovation was mediated through the creation of representational tools. After resolving the psychological obstacle of centration, there was still the matter of developing a representational system for structuring the new knowledge. The representational system allows others to develop the same knowledge on a much shorter timescale, but it is also a cultural artifact. This section of the paper serves to further explore the cultural context of human development, and how it fits into the picture of scientific development and science education.

III.2.1 A Language-based approach to development

> My dear colleagues, I am very concerned about what to say to you, because I do not know if I shall accomplish the end that has been assigned to me. But I have been told that the important thing is not what you say, but the discussion that follows and the answers to questions you are asked. So this morning I shall simply give a general introduction of a few ideas that seem to me to be important for the subject of this conference.
>
> First I would like to make clear the difference between two problems: the problem of development in general and the problem of learning. I think these problems are very different, although some people do not make this distinction.
>
> The development of knowledge is a spontaneous process, tied to the whole process of embryogenesis. Embryogenesis concerns the development of the body, but it concerns as well the development of the nervous system and the development of mental functions. In the case of the development of knowledge in children, embryogenesis ends only in adulthood. It is a total developmental process which we must re-situate in its general biological and psychological context. In other words, development is a process which concerns the totality of the structures of knowledge. (Piaget, 1964, p. 176)

Piaget himself was nervous about forging too close of a relationship between epistemology and learning. He saw the genesis of knowledge as part of the biological growth of an individual (recall that he was trained as a biologist, and originally wrote about mussels). The remarks above are from a speech given at a conference of science educators. While education must be interested in development, learning must be seen as a tandem process, and not explained through the same mechanisms. For this, there is a need for a separate theory.

Vygotsky is an excellent starting point for a discussion on learning theory. This theory introduces the cultural transmission of knowledge through the use of symbols, asking specifically “What is the nature of the relationship between the use of tools and the development of speech?” (Vygotsky, 1978, p. 19). Vygotsky’s use of the idea of ‘tools’ is broad, allowing for us to consider the types of scientific tools that have developed throughout history (Newton’s calculus is a relevant example of a tool). For instance, tool use can describe any adaptive behavior, i.e. evidence that existing resources are being used on a novel situation (e.g., either a hammer driving a nail or integrating an equation transform it to through use of a tool). Vygotsky argues that language is a focal point for organizing one’s thought, and opening up higher order processes in conjunction with a tool.

To Vygotsky, the ultimate tool in human understanding is that of language. It allows for the transformation of behaviors, and allows for planning and structuring of actions, and "independence from the structure of the concrete" (1978, p. 26). While Vygotsky is suggesting that speech is the sole motivator in the attainment of abstract thought, he allows that speech can change 'forms' through the course of development. He uses children's art as an example, observing that young children often do not name elements in their drawings until after they have completed their drawings. Older children, on the other hand, often 'name' the elements of their drawing before actually starting.

Vygotsky's place for language in cognitive development is quite strong, though the ideas have been modernized and adapted. The conversation regarding language will be reframed through a contemporary lens, but before doing so, there are other core Vygoskian ideas that, even without adaptation, have a large place in the education (and therefore science education) landscape.

The Zone of Proximal Development (ZPD) is Vygotsky's answer to the question of how an educator should structure interaction with a child. The educator is broadly defined, and need not be an adult in a traditional school, but could be a parent or even a more able peer. ZPD is built on a fundamental assumption that learning and development are intricately intertwined (Vygotsky, 1978). In a school (or any other educational setting), the teacher must be aware of a child's mental developmental level, or more simply, his individual capability given some cognitive task. The child has completed and mastered whatever intellectual developmental prerequisites exist to complete the given activity within the content domain.

But, this is not the end of the teacher's responsibility in educating the child. In his own research[7], Vygotsky found that children who were at the same developmental level when acting individually would be able to complete different levels of tasks with the aid of an adult. To make the example concrete, let us consider there are two children each of whom has a mental age of 10. Vygotsky's argument is that they cannot be educated in exactly the same manner, as one of them has a mental age of 11 when working with a teacher while the other has a mental age of 13. Therefore, in order to best serve the development of the children, the teacher would structure interactions with the children in different ways to reflect their different capabilities. In common educational parlance, as well as Vygotsky's own work, this structure provided in the educational setting by an adult or more able peer is known as a scaffold.

Piaget directly addressed Vygotskian ideas in comments preceding a Western publication of Vygotsky's *Thought and Language* (1986). Perhaps cordiality allows Piaget to acquiesce some level of

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[7] Michael Cole and the other editors of Vygotsky's work insist that he had a very thorough research methodology, which is not clear from his published work thus far translated into English (Vygotsky, 1978)

agreement with Vygotsky, although at the heart he disputes the central assertion: "It took me some time to see, it is true, that the roots of logical operations lie deeper than the linguistic connections" (p. 5). Piaget sees the origin of intellect to be rooted in the sensory motor stage of development. A continual process of decentration (spurred by assimilation, accommodation and equilibration) leads new knowledge not to be added in a linear fashion, but to be categorically reorganized periodically. Vygotsky, on the other hand argues that knowledge is structured through language. Therefore knowledge is created socially, and afforded dimension through the tools handed through society.

III.2.2 A contemporary approach to combining socio-cultural and cognitive development

Piaget and Vygotsky clearly have a central role in the study of development and the practice of education, but neither perspective is without criticism. As dynamic systems theory provides a contemporary look to stage theory, there are ideas that dramatically refresh the linguistic-based perspective of Vygotsky. The updates to the linguistic aspects of the theory will be intentionally overlooked in this paper (the ideas that stem from Chomsky, 2006, for instance, are quite interesting, but veer off course). Rather, the focus is on the cultural sphere of development, and the realization that language is a cultural artifact. The central tenant here is that one's culture guides development and learning. Therefore, in building a philosophy of science education, one must account for cultural context.

Before continuing, it is worth forming a working definition for 'culture.' Because the word can connote different meanings, and explicit definition can be helpful. Culture simply refers to the transmission of knowledge from one individual to another. Thus knowledge need not be innate, but can still be an adaptive behavior. Culture is not unique to humanity, there is, for example, evidence that primates exhibit culture (Goodall, 1986). In this case knowledge can take the form of physical tool use, and is behavior that is not innate to the animal. The knowledge is transferred between individuals of the species.

All humans participate in culture, and therefore are acquiring information from their surroundings. Thus, it is possible to say that there is a contextual context to development. Human development of an individual simply cannot be separated from context; a context cyclically shapes the individuals that comprise it. Culture is sometimes used to talk about differences between human groups (e.g., Japanese culture, Italian culture, etc.). Different groups of individuals do have different shared traditions, thus differentiating the cultures is appropriate. Here, however, I am more interested in the mechanisms under which cultural knowledge is transmitted, which presumably could be shared between cultures. Considering the differences between diverse cultural groups is an important second step that could be taken on.

Rogoff (1990) provides a framework for observing cultural development and learning, describing three spheres of concurrent development: apprenticeship, guided participation, and cultural appropriation. We could potentially consider these processes on the same basic level as assimilation, accommodation, and equilibration, describing how development can take place. As an aside, it is interesting to note how modern research reflects its roots. Piaget attempted to quantify his observations to the best of his ability, and contemporary neo-Piagetian approaches continue looking at development in a very quantitative manner. Vygotsky's descriptions of his research are highly qualitative. Contemporary socio-cultural research mimics this approach, though in fairness, the modern qualitative approach is far more disciplined.

Apprenticeship is perhaps the major theme in Rogoff's work. As she describes it:

> The notion of apprenticeship as a model for children's cognitive development is appealing because it focuses our attention on the active role of children in organizing development, the active use of other people in social interaction and arrangements of tasks and activities, and the socioculturally ordered nature of the institutional contexts, technologies, and goals of cognitive activities. (Rogoff, 1990, p. 39)

The apprenticeship model suggests active individuals who take ownership and 'organize' their own knowledge. Yet at the same time, the individual has access to support from the community. But there is no reason to limit the notion of community supports to actors such as parents or teachers. One can be an apprentice to any artifact that can convey knowledge: a textbook, an online community encyclopedia (caveats about understanding the source applies, but again, that counts as cultural knowledge), or even more mundane everyday objects. An artifact, even as mundane as a chair (it does 'arrange' or 'organize' a specific task: sitting), can convey information about what to do with it, implying a brief, unremarkable, but very real apprenticeship (Gibson, 1986).

Rogoff cautions against putting traditional limitations on the idea of apprenticeship. As Rogoff explains, an apprenticeship, in her theory, is not strictly a one-on-one encounter (thus students in a classroom are engaged in apprenticeship) and there could also be multiple 'experts.' When a group of novices work together, their resources are pooled together, and at various times different individuals can take on the mentor role or the apprentice role. John-Steiner (1997) points out that through the apprentice-mentor collaboration, the apprentice can surpass the mentor, and uncover knowledge that remained hidden to the mentor[8].

In the field of science education, the apprentice-mentor relationship is an important one to understand. Not only is the student expected to learn from the teacher, but also from the various lab

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[8] Sorry for the frivolity that follows. One day maybe you'll see Understanding Socio-Cultural Cognitive Development through *Star Wars*, by Jason M. Kahn.

materials, demonstrations, and texts that are utilized in the course of instruction. The displays used to communicate data (e.g., graphs) can play a part in a child's learning.

Rogoff's second sphere of development, guided participation is a statement not only about the role of the mentor, but of the entire community. A teacher frames the interactions (learning encounters, in today's vernacular) that a student will engage in. Knowledge is 'guided' to some logical end point. But more than that, the learner is awash in a world of symbols, signs, words, images, and actions that shape the terms in which the world is seen. A society pushes its members to think in a way that works within the larger system, using symbols that make sense. Guided participation is another useful framework not only for science education, but also for the larger field of education. Guided participation gives structure to the common sense idea that a chosen pedagogy will affect how learning proceeds.

The third sphere of development, cultural appropriation is an important process that can easily get left out of the discussion on education. Each culture is, after all, made of a collection of individuals, each contributing to the culture. There are certain events that will lead a culture to appropriate a new idea and grant it wider cognition. The case of Newtonian physics is an example of this. Newton developed a science that went beyond what any of the peers in his culture were capable of doing. However, with the veracity of Newton's work never in doubt, his peers were quick to adopt his individual accomplishment into the scientific culture at large. Feldman and Goldsmith (1991) discuss this process in his discussion on creativity. Individuals with supremely unique talents are able to drive understanding on a platform larger than themselves.

The processes identified by Rogoff find experimental proof in studies of children in multiple, far-flung cultures (Rogoff, Mistry, Goncu, & Mosier, 1993). While examining the daily activities of toddlers and those who look after them in the United States (Salt Lake City, Utah), Iran, India, and a rural Mexican town, researchers continually find examples of apprenticeship and guided participation. Children develop different behaviors, sometimes distinctively different than what a strictly Western stage theory would predict. However, all of these behaviors can be explained though the lens of how the culture structures the interactions that the child has with the environment.

III.2.3 Why bother with a cultural framework for science education?

The cultural context of development adds another layer of complexity to education. The layer may seem overly complex: many students in classrooms share similar backgrounds. With a shared background would seem to come a shared epistemology. Most science educators will not find themselves in rural villages on far corners of the earth, and it would seem to make sense to stick with to Western view of development, especially if it can accurately predict the behaviors of the students who will actually be arriving in the classroom. Why, then, spend time considering what influences a culture has on learning and development? Especially when considering mathematics and science, which should be ideal meritocracies: the best ideas should rise to the surface regardless of cultural framework.

There are several compelling reasons to pay attention to a cultural sphere for development, and they come from a variety of perspectives. First, there are many examples of science education failing women and minorities. This is a failure for the entire scientific community; it stifles a diversity of ideas that could otherwise benefit progress. To understand how this can happen, it makes sense to probe the overlap of two sub-cultures. Those of the scientists responsible for building the pedagogy and the students the educators are failing. Overlapping cultures often lead to a sort of tension that stifles the stated goals of education. One culture is trying to transfer knowledge under memes that make sense to them, while the learners struggle with information being presented in an unfamiliar mode. The second consideration is that it is impossible to do education research, science education research included, without considering the classroom to be a micro-culture. In Western culture, most learning takes place in a classroom, not a laboratory. A classroom has a number of actors, and is a microcosm of cultural knowledge transfer.

Minorities in United States (US) education have been the topics of books, scholarly articles, documentaries, newspaper articles, presentations, Ph. D. dissertations, and every other conceivable form of media that can transmit knowledge, opinions, or research. Simply, this is because people of lower socio-economic status (SES) in the United States do not achieve as highly on standard measures as upper-class peers. This is true in literacy (e.g., Aram & Levin, 2001; Purcell-Gates & Dahl, 1991). This is true in mathematics (e.g., Crane, 1996; Moses, 2002; Tate, 1997). This is true in the sciences (e.g., Tate, 2001). In a separate discussion, one could consider that the academic assessment strategies themselves are not fair to underprivileged students (or that the tests are worthless assessment measures of all students), but the evidence for an achievement gap is broad enough to simply be discounted because of sub-optimal testing procedures.

Beyond the problems of minority achievement in science, women do not seem to be participating in science, mathematics, or engineering programs in the same numbers as male counterparts (Seymour, 1995). It can be further added that the women who do achieve high-level degrees in the sciences are less likely to persist in their field (Xie & Shauman, 2003). Further, children are making decisions about these fields as potential careers as early as middle school, and showing little interest in careers in science (Tai, Qi Liu, Maltese, & Fan, 2006). Finally, the pressures that lead students to make a career choice are exerted as early as the elementary grades, especially in relation to self-efficacy (Bandura, Barbaranelli, Caprara, & Pastorelli, 2001), stressing the importance of fostering success at the earliest levels. Since we do not see women and minorities following science tracks in equal numbers to men, the conclusion is that these are male-driven fields, with male-driven pedagogy, and are somehow exerting a (perhaps hidden) pressure designed to preserve the status quo.

Delpit (1995) gives a framework to consider the problem, though in different terms. Delpit's work concerns the failure of the US education system to educate its minority students. This failure, as seen, pervades through the system regardless of content. Delpit's work can easily be adapted to the problems facing science education by considering that in each case, there are examples of students being shut out of an education. Her work discusses the collision of two separate cultures, and the problems that this can create in the classroom.

Delpit discusses the 'culture of power,' which for all the dramatic flair the words impart, is truly a thesis of cultural inertia. Consider that in a given society a collection of individuals is typically able to consolidate power, not through insidious means, but simply because this is how societies organize themselves. A collection of individuals, outside of the culture, may seek to participate in the society. Delpit writes about a white middle class consolidating the 'power', while African Americans desire to participate.

If a member of the culture of power, every aspect of life prepares one for participation in the culture at large. At home, parents transmit norms that are valued. Then at school or at work, these people understand the subtleties that develop within the language and are well equipped to get ahead. These amount to 'codes of power,' a set of keys to participating in a larger culture. The outsiders never pick up on these cues, and the penalties are lower grades and/or lower wages.

These ideas can be explored experimentally by qualitatively examining the performance of students from one cultural background who enroll in the schools of a second culture. For example, Heath (1989) describes the traditions of children in predominantly black communities in skills that generally predate literacy. She finds that these traditions are often at odds with the oral and literacy skills valued in mainstream education. Superimposing the philosophy of a culture of power, it is impossible to value one set of traditions over another. However, the mainstream traditions enable participation and economic success in the larger, mainstream society.

One can alternatively 'blame' members of the minority culture for failure to adapt (e.g., see Rodriguez, 1983; although it is arguably a simplified characterization of a nuanced position) or the mainstream culture for not understanding how to educate a minority culture for mainstream participation while honoring differences, consistent with Delpit's position. Pianta and Walsh (1996) add that one could blame the individual child (presumably for the sake of completeness; the perspective is odd for a systematic problem, and they ultimately prefer engaging the problems by looking at contextual factors). But addressing fault for a large-scale problem is not a useful construct, especially in relation to the topic of science education.

Barton and Yang (2000) followed one inner city, homeless high school student through his science education experience to further understand how the 'culture of power' affects science education. They argue that culture portrays science in a very specific way: white, male driven, static, and only accessible to the brightest minds. In their case study, the student they follow expresses a passion for observing the natural world, but finds that his interests do not fit well with the values of the school. The researchers argue that the experience of their subject is one story among many more.

There is no explicit malice in the education of Barton and Yang's case study student, nor in the education of the likely countless similar students. The culture of power is not an indictment of mainstream culture, but a statement of how outsiders can feel left out of a culture. Barton and Yang focus on the popular portrayal of scientists, and end with the assessment that this is part of the problem. However, even with mischaracterizations of scientists, there are elements of science that form a very real subculture. Learning how this subculture interacts with the culture of others is an important part of building truly open science pedagogy.

However, the problems run deeper than a stereotype cultivated through mass media. Geertz (1973) defines culture eloquently:

> The concept of culture that I espouse, and where utility the essays below attempt to illustrate, is essentially a semiotic one. Believing, with Max Weber, that man is an animal suspended in webs of significance that he has spun, I take culture to be those webs, and the analysis of it not an experimental science in search of law but an interpretive one in search of meaning. It is explanation I am after, construing social expressions on their surface enigmatical. But this pronouncement, a doctrine in a clause, demands itself some sort of explanation. (p. 5)

The more traditional definition of culture is less opaque, in this case it is used to mean practices passed from one individual to another. However, by referring to it as the webs that connect an individual to a greater meaning, one can imagine a scientist, suspended in a collection of theoretical and experimental traditions, carrying forward in the pursuit of new knowledge, at the same time building more webs.

Those who practice science are members of a specific culture, or at the very least, a subculture (by which is meant a second culture existing within a larger culture). As a consequence of this fact, and no other prejudice, there will be certain codes that fellow scientists expect to be followed in order for participation in 'science.' These codes can be obvious an unstated to those who are already in the field, but are mysterious to outsiders. Women and minorities, who are not participating in science at the same rate as white male counterparts, are prominent examples of these outsiders to the subculture.

There is no easy or apparent solution, or even one common cause for the problem. While minorities do not achieve on the same level as mainstream students, women often do, but show less interest in pursuing scientific careers (Catsambis, 1995). Jones, Howe, & Rua (2000) research is similar to Catsambis's, also adding that in the students they surveyed, the interests claimed by male students were more in line with the curriculum than those of women. While there is no reason to see the scientific method itself as gender biased, the content that a textbook chooses to highlight certainly can be gender biased.

As an example, many modern physics textbooks deal with space travel in a discussion of relativity (e.g., Krane, 1996). Time dilation is an important concept, though the specifics of this concept are not important here. The presentation can quickly become bogged down with rockets and space travel, rather than focus on the content itself. A teacher may have an affinity for a certain presentation, but it is important not to be overly specific, as a portion of the audience may experience a disconnect to the chosen context.

In Davis's (2004) genealogy of teaching, he critically analyzes different traditions of thought, and how they have split throughout history. In doing so, he may provide clues about how different cultures could have difficulty in science classrooms. While Western tradition has roots in rational and empiricist discourse, which facilitate scientific inquiry, other traditions of thought do not. In Davis's thesis, a student could have a worldview incompatible with the philosophy and practice of science. This would make an educator's work very challenging: adopting a scientific outlook may involve the student abandoning a deep-seeded worldview.

Taking a cultural view of science education empowers an educator to understand the students at a much deeper level. It allows the educator to make judgments that will allow him or her to best facilitate the learning of both scientific concepts and the process of scientific inquiry in general. However, a cultural perspective on science education also provides a framework for understanding the processes that happen within a classroom.

Bronfenbrenner (1976) makes the commonsense observation that education happens within a classroom. While the idea may seem trite, much of the work that goes into understanding child learning happens in psychology labs. Consider the work of Piaget, held in revere in this discussion, which nary enters a classroom. This practice extends to nearly every study of cognitive development discussed thus far, except for those that explicitly looked for a cultural context to cognitive development.

Bronfenbrenner outlines twenty propositions for undertaking educational research, and they should readily be applied to science education research. While it is not the place to outline all twenty propositions, they can be paraphrased to conducting research in the most natural setting possible. So, if one undertakes to understand how children learn, we are best served by going to places where students learn. If one wants to develop a new curriculum, then the curriculum should be observed being implemented in a classroom, not a laboratory.

These guidelines only make sense when one considers that there is a cultural aspect to learning. They can be extended to science education research by remembering that: (1) science education is still an education process; and (2) that the practice of science represents a specific subculture. In both research and practice, one cannot ignore the context in which the learning takes place.

III.2.4 Extending scaffolds, ZPD, and socio-cultural theory into inquiry-based science

Inquiry science is a specific method of teaching where students are expected to ask 'authentic' questions and use 'authentic' methods in the process of their science education (White, 1993). In inquiry instruction, there is an emphasis in students getting hands on with the tools of science. These are laboratory tools, representational tools, and methodological tools. Inquiry can be viewed as a partner to the conceptual approach to science education, often with similar goals and methods. However, where the conceptual approach of science education was born in a tradition of individual cognitive development, the inquiry approach reflects community-driven values of its socio-cultural roots.

Inquiry-based investigations in science have a lengthy history. John Dewey (1916) noted that a theoretical knowledge of science leads to a disconnected and hollow knowledge, while the vast majority of students have no need for the intricacies of a given content, and would be better off appreciating scientific methodology as opposed to any specific content. This paves the way to a content-leading-methodology approach as opposed to a methodology-to-content approach more in line with fostering a deep conceptual understanding. In practice, this leads to educational conversations such as Hapgood, Magnusson, and Palincsar (2004), a study of elementary students exploring the relationship between mass, momentum and velocity. While the curriculum demonstrated that the child could master the content as the researchers presented it, the ultimate conclusion was that the children mastered process goals such as using data and conducting investigations.

However, in determining whether scientific inquiry is indeed a tool that can frame other learning, one must consider how much the idea of scientific inquiry as a tool can be stretched. Vygotsky limited tool use to language; however, interpreting Rogoff's work gives room for many more culturally appropriated tools. It is easy to stretch this into a mathematical domain (perhaps considering mathematics to be a type of language), including even with visual representations. Ochs, Gonzalez and Jacoby (1996, in Nemirovsky, Tierney, & Wright, 1998) write:

> Graphic displays thus not only provide physicists with a cognitive domain to inhabit and wander in, they also transport physical phenomena into the perceptual presence of

> physicists and serve as a locus in which the physicist and the phenomenon can be brought into symbolic contact with one another. Cognitive and gestural orientation to a graphical representation, therefore, make possible for physicists to symbolically in the physical events represented by the graphical space.

Physicists, and indeed all scientists, can use graphs (and presumably other tools as well) as a transformative tool, much in the same way that Vygotsky writes about language transforming the ideas of students. It still seems like a stretch to consider any cultural artifact as a representational tool, ready to transform knowledge, an argument that Pea (2004) acknowledges in stating that perhaps the term scaffold is thrown around too casually.

On the question as to whether having an inquiry-based knowledge of science can transform knowledge, there does not seem to be a conclusive answer. However, as evidenced through the vast amount of research concerning inquiry-based science ((Singer, Marx, Krajcik, & Clay Chambers, 2000; Welch, Klopfer, Aikenhead, & Robinson, 1981) are starting points to a much larger field of research), the general consensus is that inquiry-based methods are an invaluable part of the educational process.

Inquiry methods are not a panacea, and serious questions can be raised as to whether inquiry methodology leads to an increased understanding of scientific concepts. Klahr and Li (2005) have demonstrated that in some cases, direct instruction has been more effective in teaching concepts than inquiry methods. Recall in science education that direct instruction was found to be a disastrous teaching technique (e.g., Hake, 1998). This is unnerving to say the least, as inquiry has the potential to go even further awry. However, the authors do stress the need for a limited interpretation, pointing to the fact that their studies concerned only a small number of students. There are also sufficient examples of successful inquiry classrooms to believe that Klahr and Li's findings represent a hard rule rather than a warning of consequences of a poorly constructed inquiry lesson.

Nersessian (1989) argues that to understand conceptual change, one must look at the reorganization of language related to the change, a quintessential Vygotskian perspective. The argument is that language frames understanding, and one must adopt the ontology of a scientist in order to truly espouse the conceptions of a scientist. Wiser and Amin (2001) have demonstrated how ontologies can be used to help learning in the case of heat and temperature. These two ideas are often mistaken, but with a careful approach, they are able to 'induce' conceptual change concurrent with the shifting ontology.

Chi and Roscoe (2002) understand 'misconceptions' through ontologies. (As an aside, one who adopts a social perspective can get away with the term 'misconceptions,' even though it is not favored in this discussion. A community sets a preferred privileged conception – for example, a Newtonian conception of classical mechanics – and those who hold an alternative are 'wrong' in that they can not participate in the mainstream [sub] culture.) From this perspective, students who espouse misconceptions are simply mislabeling phenomenon. To draw from the examples already discussed within Newtonian mechanics, the argument is that students do not correctly label ideas that they do understand, such as movement. Reclassifying these concepts is an intellectual shift, and requires little cognitive effort from the student. However, there are times when students possess no appropriate ontological category (e.g., force), and their current classification for such ideas is counterproductive. This process is much more difficult, since the student must develop the correct ontological category.

III.3 Rationalizing constructivist and socio-cultural theory

Thus far, there have been two complimentary philosophies of science education put into place. One contends that a student constructs an understanding of the world around them through an equilibration of external factors (assimilation) with internal processes (accommodation). This leads to a bottom-up view of conceptual science: students must build an understanding of specific concepts through either physical (a 'hands-on' approach) or cognitive (a 'minds-on' approach) interaction. In this bottom-up approach, meaning is ultimately derived from and by the student.

The second philosophy contends that in order for student thought to have any meaning, it must fit into culturally developed hierarchies. In this philosophy, science itself is treated as a cultural enterprise. In order to participate in science and learn scientific concepts, students must adapt to a scientific world-view. In this world-view, the scientific method and inquiry-style learning are the keys to scientific learning. This is a top-down approach, as the tools of a scientific culture are already in place and the teacher attempts to transmit these tools.

Since these philosophies have different underlying assumptions about human learning, they are difficult (though not impossible) to reconcile. However, an educator is fortunate in that there is no need to reconcile two different theories of mind. An added benefit is that both theories will likely undergo serious revisions as researchers can peek further and further into the brain. Being theoretically unencumbered does not mean that there is no opportunity to draw on the major successes of both theories.

Conceptual-based education has led to a large amount of successful pedagogical strategies and metrics. These strategies are the subject of the next part of this paper. The caveat is that the strategies are heavily dependent on content; the educator must have a rich grasp of the material they propose to teach. This leads to historical-style studies as the one that began this discussion, as the content not only guides the concepts, but also informs the educator regarding how the genesis of the concepts might occur. Yet, in the end, the educator must provide the student with the opportunity to learn the content through offering appropriate tools and resources.

Allowing for cultural considerations in development and learning can reinforce this strategy. It informs the educator that the same strategy will not work for all students, as students bring different resources and background into the classroom. In fact, while the instructor may be able to offer a passionate approach, it is entirely possible that the instructors' passion will not resonate with all students. While this is a statement of cultural awareness, individual cognition has not been contradicted. The student, as an individual, brings experiences into the classroom that may differ from both peers and the teacher. Cultural considerations also give a framework for considering and remedying some of the more pervasive problems in science education, such as the fact that not all students are receiving an equal education.

Part IV:
Several Research Validated Strategies in Physics Education

There is a certain temptation to embrace a clockwork model of cognitive development. Tiny, psychological gears and cogs move in concert. The cognitive scientist can probe the structure, and attempt to develop relationships among the individual pieces. Like Newton's universe, the clockwork brain can be understood through a series of meta-laws establishing mathematical relationships. With the full command of how the mind works in its physical and social context, outcomes can be predicted (of course, students possess scientific 'misconceptions,' these are artifacts of circumstances X, Y, and Z). Learning becomes prescriptive. Shift the cogs around, and suddenly the mind exhibits a Newtonian conception.

The clockwork metaphor embraces all of the epistemologies discussed in the previous section. Constructivism, socio-cultural theory, theory-theory, phenomenological primitives, and dynamic systems are all alike in their prediction of an orderly mind that can be elegantly described. Of course, this is a necessary feature of any scientific theory. Yet when it comes to describing individual learners, theory can seem to go awry as educators attempt to apply a set of ideas not only at odds with each other.

These factors are not only students who do not fit neatly into existing theory. The factors include administrative pressure (which includes standards), available resources, and time constraints. The practice of teaching operates in a different sphere than cognitive development. And while theories of learning have clear applicability, practice can be far from ideal.

However, the study of teaching can also be viewed in an empirical manner. Best practices emerge, even absent the same clockwork predicted in developmental literature. Teacher research literature has documented countless examples. I cannot (nor do I want to) document them all. The subset of research studies is slightly less large when focusing on science education. The tendrils of Isaac Newton run deep into this paper. After establishing the primacy of Newtonian mechanics in the genesis of physics, and having tied these concepts to the study of epistemology, I will look at education from the perspective of teaching Newtonian mechanics. The methods presented are still relevant across a wide variety of content.

IV.1 Measuring a concept

IV.1.1 Physics Education Research

Physics education research (PER) is a very narrow discipline within science education research. As the name implies, PER is specifically interested in the education of physics. As physics instruction typically happens at high school and undergraduate levels, these students are understandably the main foci of education researchers. Further, introductory topics have garnered far more attention than advanced topics. Introductory topics are typically considered to be mechanics and electro-magnetism, with 'modern' topics being the domain of advanced study. As will be seen, PER has dovetailed nicely with the advent of conceptual pedagogies.

Early research in PER centered around a common theme. Students were (and still are) developing a quantitative grasp of introductory physics concepts. However, they do not display an ability to qualitatively reason about these same topics (e.g., Clement, 1982; diSessa, 1982; McCloskey, 1983; Trowbridge & McDermott, 1980; Viennot, 1979). This is not to say that students do not have qualitative ideas about physical concepts. As has already been discussed, the qualitative ideas that the students espouse have parallels in historical formulations of physics.

IV.1.2 Conceptual Metrics

As already discussed, an alternative conception is merely a statement that the student's conception does not line up with accepted scientific theory. As we shift our attention to education, it must be further reinforced that the alternative conception does not connote that the student has no conception at all, merely that it is distinct from what the educator is striving to instill. Viennot (1985) transcribes student discussions with one another and is able to qualitatively record peer interaction. In one example, he relates the story of students who believe that any observed velocity connotes a force. In a presented example, students discuss the flight of a tossed coin, reasoning that there must be a force in the upward direction until the coin stops its upward movement. Further, the students reason that this force must be greater than gravity.

Hammer (1994) presents an alternative view of conceptual knowledge. Rather than focus on conceptual knowledge, he chooses to focus on epistemological beliefs as a type of (meta) conceptual knowledge. Through interviews he finds that students do not see physics as a unified field, but as a disparate set of unrelated equations. Many students feel that learning physics involves learning equations and applying them: students are not even approaching the content with expectation of acquiring deep conceptual knowledge. The students' conception is that conceptual knowledge is unimportant in a high school physics class.

Qualitative approaches can become cumbersome with large samples of students. Within the domain of force and motion, there are two common quantitative approaches, the Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992) and the Force and Motion Conceptual Evaluation (FMCE) (Thornton & Sokoloff, 1998). Both of these assessments are multiple-choice evaluations. Responses to the FMCE can be broken into different strands, such that educators can individually look at a student's understanding of velocity, acceleration, Newton's first and second laws, and Newton's third law.

The format of these assessments–multiple-choice–has risen the ire of certain reform educators. Scouller (1998) describes how students prepare differently for multiple-choice assessments and essay-response assessments. In essay-response, students adopted 'deep strategies' and 'deep motives' for learning, meaning that they strived for content understanding and making connections among topics covered in class. In multiple-choice, students' preferred 'surface' techniques: being able to produce what they learned without a broader understanding. Linn, Baker, and Dunbar (1991) repeat many of the same concerns about multiple-choice testing in a review of literature, finding that open-ended assessment is a much better window into the students' thoughts.

There are certain mitigating factors in opting to make use of multiple-choice measures. In the case of both the FCI and the FMCE, there are ample qualitative data lying behind the quantitative metrics. The researchers validated their questions against student responses, and echoing the results that have already been presented, were able to conclude that students answered conceptual questions in predicable patters. In the case of the FMCE, there are many choices (up to 10), to try to capture student ideas. Students can also explicitly reject all of the choices, an option that is rarely acted upon.

Hestenes and Wells (1992) directly address the concern of 'teaching to the test.' This is a common meme used against standardized measures which implies that the teacher will teach the student to only address the content presented on the assessment, and then teach no further. First, it is important to note that this implies a poor test. If the test is reasonable at measuring the teacher's goals (as they would be independent of the test) then 'teaching to the test' is just simply 'teaching.' The creators of the FMCE argue exactly this line of logic. As the FMCE measures a student's conceptual understanding of physics, teaching to this particular test would be successful teaching. Hammer (1996) adds that individual scores on a conceptual multiple-choice test may not be entirely relevant, but in aggregate can inform instruction and pedagogy.

Upon accepting that quantitative conceptual metrics are valid, it is useful to establish a framework for comparing curricula. Often, classroom performance is reported in terms of normalized gain, a construct developed to measure how much a student learned, and not end points in isolation. If a student gets high marks on a posttest, while clearly a good thing, it does not necessarily translate to learning. After all, they could have had the exact same score on the pretest, and thus showed no growth. Normalized gain addresses this concern. A student who goes in knowing 80% of the content and leaves knowing 100% of the content has a normalized gain of 1.0; they learned everything asked of them. If the same student had a posttest score of 90%, then they would have a gain of 0.5. If a student had a pretest score of 20% and a posttest score of 60%, they likewise have a gain of 0.5. These numbers are not useful on an individual level, which is why the gain for the entire class is examined in aggregate. A single number reflects the effectiveness of instruction, but must be put into context. One must know the gains of traditional instruction in order to be able to assess the effectiveness of a new curriculum.

Bao and Reddish (2001) developed a sophisticated method of measuring conceptual understanding, though it is expensive in terms of the time required to administer. Focusing on only one concept (Newton's 3rd Law), the researchers qualitatively broke student reasoning into four distinct categories. The researchers then rewrote the third law assessment questions from the FMCE to develop 16 questions that individually focus upon each one of the four categories. Thus, they can find if the student can apply the concept correctly in some instances, but not in others. The analysis leads them to be able to develop a 'model state' of each student and the class in aggregate, a quantitative measure of a conception.

This model state has roots in quantum mechanics. This branch of physics dissolves notions of absolutes, and describes physical events only in terms of probabilities. To be concrete about this, there is a probability that the reader of this paper is sitting on the chair. There is also a probability, infinitesimally small, that the reader will fall through the chair, and is on the floor. Bao's hypothesis is that concepts are best measured in a similar manner. That is, one cannot say that the student has one definite conception. It is better to build a model state for the student, which defines the probabilities that the student will express a concept in a given context.

Qualitative assessment is the first choice for student assessment of conceptual knowledge. In cases with limited samples, it provides a more nuanced picture of student conceptions. However, in measuring instructional effectiveness on a large scale, quantitative assessment is more practical and effective. The quantitative assessment must be carefully designed, and fairly represent every foreseeable conception. This allows for much larger numbers of students to be assessed, and a much larger scale evaluation not only of individual students, but of curriculum and pedagogy.

IV.2 The Failure of Traditional Instruction

'Traditional instruction' does not have a single definition. In this paper, it is classroom instruction that is undertaken without being informed explicitly through empirical means. Most forms of instruction have a feedback mechanism built in; teachers are expected to assess student progress throughout a course. However, this assessment is not often rigorous, and its purpose often does not stray from the stated goal of measuring students' progress as opposed the effectiveness of instruction.

In undergraduate lecture halls, traditional instruction often refers to a specific pedagogy. A lecturer arrives in the hall and goes over material in a highly quantitative way. There is little engagement with the students in the classroom. In some cases, there are demonstrations, though once again, they are not presented interactively. There may also be laboratory assignments, often of the 'cookbook' variety, where students are expected to recreate an experiment with a known result from a lab manual.

Using this definition of traditional instruction, Hake (1998) created a large sample, two-category comparison of traditional versus interactive engagement style instruction of undergraduate physics. Interactive engagement curricula are reform in nature, and demand some level of intellectual engagement from the student. They are on the whole very successful, and discussed later in this section. Hake looked at gains on the FCI, discovering that in fourteen 'traditional' classrooms encompassing over 2000 enrolled students, normalized gain was 0.23±0.03. In forty-eight interactive engagement courses, with over 4400 students, normalized gain was 0.48±0.14. In brief, gain was twice as high, or students learn twice as much in interactive engagement classrooms, as measured by the FCI.

There are serious caveats with regard to Hake's data, the biggest being that it was self reported, introducing a bias. These scores likely represent an upper end of results, since instructors are most likely to report their best outcomes. There is also no mechanism for auditing 'interactive engagement.' Classrooms that used the technique extensively could be placed in the same group as classrooms that used the technique once over the course of instruction. Yet with the large sample and gains twice as large for interactive engagement, there is a strong reason to believe that traditional instruction is not the most effective form of physics instruction.

In a carefully controlled environment, (Redish et al., 1997) echo the comparison of interactive engagement to traditional instruction. The research group compared a specific interactive engagement strategy versus traditional lectures, but was free of the limitations of survey reported data. They found much the same results as Hake, finding that over five separate classes reform curricula led to gains of 0.35 while traditional instruction led to gains of 0.18, and that no instructor had better results in a traditional format versus an interactive one.

Many researchers have offered theories as to why traditional instruction fails. Some research looks at student expectations and resources and how this affects instruction. Elby (1999) establishes that high-school students are often interested in good grades and not in a deep conceptual understanding of physics. A quantitative presentation feeds into their epistemological belief that a superficial understanding of the topic is sufficient, while not encouraging them to form a deep conceptual understanding. Van Huevelan (1991) adds that most physicists do not approach problem-solving tasks in a quantitative-first manner, favoring heuristic tools such as diagrams to qualitatively understand a problem before working though a problem quantitatively. Chi, Feltovich, and Glaser (1981) provide more measure to how different experts and novices work through physics problems, but the larger point is that novices are failing to gain expert-like approaches even after instruction from 'experts.'

Building on the work of others Redish, Saul, and Steinberg (1998) identify six dimensions for classifying student expectations. *Independence* refers to a student's belief regarding physics as either a set of knowledge to be constructed or whether they expect to receive information. *Coherence* refers to a student's belief as to whether science is a collection of unrelated ideas of a single related entity. *Concepts* refers to a student's understanding physics as either conceptual or as a more superficial set of equations. *Reality Link* describes whether students believe that physics describes the physical world, or if they believe that it is a special case of the physical world applicable only in laboratories. *Math Link* measures student opinions on the mathematical formalism in physics and whether it conveys useful information or is simply a way of 'calculating numbers.' *Effort* is a measurement of how hard students believe physics should be.

These dimensions represent a fair portrait of how research paints the factors leading to student expectations in introductory physics. The construct of 'math link' is perhaps the most suspect, since conceptual education strives to build an understanding of the physical world that cognitively transcends mathematical representation. Of course, the mathematical formalism is invaluable in communication, but it is a model of the physical world.

Thornton (1992) summarizes in four generalizations the difficulties introductory physics students have in understanding physics.

> (1) While rote use of formulas is common, a coherent conceptual framework is not typically obtained; facility in solving standard quantitative problems is not an adequate criterion for functional understanding.
> (2) Growth in reasoning ability does not usually result from traditional instruction.
> (3) Connections among concepts, formal representations (algebraic, diagrammatic, graphical), and the real world are often lacking.
> (4) Teaching by telling is an ineffective mode of instruction for most students. (pp. 48-49)

These four statements are meant to gather consensus around major themes of research in physics education, and move away from concerns about individual student cognition and into strategies that can be applied for entire classrooms. This is not to say that individual cognition is not important, but that it can lead to fragmented efforts rather than community-wide consensus on effective pedagogy. These four principles also lead to reform curricula that have been much more effective than traditional physics instruction.

IV.3 Examples of reform curricula

IV.3.1 Interactive Engagement

Interactive Engagement (IE) is a specific pedagogy used in physics instruction. The most commonly noted interactive engagement approach is Mazur's *Peer Instruction* (PI; 1997), though there are others. In PI, Mazur makes an effort to emphasize conceptual understanding as a path to quantitative understanding of physics. Over the course of instruction, students are presented with conceptual questions. Students develop an individual answer and relay the answer to the instructor. After this, they discuss the answers in small groups. Only after working as a group is the answer presented to students. After the short, small group discussion, the instructor takes a poll, reviews the correct answer, and moves on to the next topic.

Crouch and Mazur (2001) report an observed gains increased from 0.23 to 0.48 on the FCI after introducing PI. One common concern with a conceptual approach to science education is that mathematical problem solving ability suffers. Using the Mechanics Baseline Test (Hestenes & Wells, 1992), Crouch and Mazur reported that gains in mathematical problem solving were 66% before PI was introduced, 72% in the immediate subsequent year and reached a peak of 79%. A structured conceptual approach not only increases a student's conceptual understanding of physics, but also their ability to use mathematical problem solving skills.

IV.3.2 Technology-aided interactive instruction

PI does not require any exotic technology to enter the classroom, which has both advantages and drawbacks. Many of the questions are multiple-choice, thus students can relay their answer simply by writing on a placard and raising it so the instructor can see. The procedure can be technology-augmented, for example 'clickers' are devices that electronically record and tally student votes. However, the technology is not required, making for a very low barrier for a teacher to bring research-validated practices into the classroom (for my purposes, technologies that allow for completely new possibilities are more interesting). The drawback is that without a suitable testing framework, the answers to Mazur's conceptual questions must be taken on faith, an anathematic proposition given the nature of science. Actually testing the conceptions requires experimental equipment. Using the experimental equipment for meaningful learning requires thought out experiments.

These experiments must also be represented in a meaningful way to the students. Reaching back into the conclusions from the history of science, new modes of thinking arrived with a new set of representations. These representations afforded an understanding across a broad audience to content that had previously eluded generations of thinkers. Technology allows for scientific representations to be presented to students in novel ways, building conceptual understanding by giving concrete definition to the concept.

Sokoloff, Thornton, and Laws (2004) introduced a curriculum called *RealTime Physics* (RTP) based on the idea of a microcomputer-based laboratory (MBL; Thornton & Sokoloff, 1990
). The RTP and MBL curricula address the concerns of the Mazur approach, making use of technological tools that represent physical phenomena. At the heart of a MBL are two key components: probeware and real-time data collection software. Probeware refers to specific hardware that attaches to a computer and collects data, relaying it to the computer. Examples include a motion detector, which can detect distance from an electronic eye, or a temperature probe, which collects temperature data. Probes interact with real-time data collection software to present a real-time representation of the data. This could be just a digital readout, but the most powerful representation is a real-time graph. The computer automatically plots the probes recorded value versus time, as data is recorded. More sophisticated arrangements allow for multiple probes to be attached, and different dimensions to be looked at in tandem.

RTP follows a rigorous script. First, a phenomenon is described to the student, for example, a cart rolling up a ramp. The student is asked to individually predict what the distance-time, velocity-time, acceleration-time, and force-time graphs will look like (different units may call for different combinations of graphs). After making an individual prediction, the student works with their lab partner to compare predictions and discuss. The student then collects data using the probeware and software, creating the graph in real time. The student records this graph, and follows up the lab with questions for discussion. A lab consists of a sequence of demonstrations, but each demonstration is very focused. The phenomenon is carefully constrained such that the student's prediction and recorded results only address a single concept.

The real-time graphing is a powerful cognitive tool. Brasell (1987) demonstrated that it facilitates conceptual understanding of both science and graphing concepts. Undergraduate students were presented with real-time graphs, graphs delayed by 15 seconds, and graphs where the students had to make the plots on their own. The results were striking, in that even desynchronizing the graph by 15 seconds impaired conceptual learning, while a total decoupling had an even more dramatic effect.

Nemirovsky et al. (1998) come to much the same conclusion. In two in-depth interviews, two young students (ages 9 and 10 years old) use a real-time graphing configuration to explore body motion and graphing. The students move their bodies in tandem with a motion detector, creating a real-time graph. The interview framework allows the researchers to gain deep insight into these particular students' thought processes, and they note that the students seem to fuse the idea of the graph being a symbolic representation with shape and as a story reacting to their motion. The graph becomes a narrative tool, which addresses one of the conceptual shortcomings that even undergraduate students have with understanding graphs (McDermott, Rosenquist, & van Zee, 1987).

The picture that emerges is that RTP has two modes of operation. First is the element of interactive engagement. Peers are learning from their discussions with one another. Second is the representations afforded by real time graphs. These representations are more powerful than simple static representations, and allow the student to relate to physical phenomena as the phenomena unfold.

Left out of this picture is the action of the prediction, which is an emphasized piece of RTP. Predictions have clear roots in the philosophy of science. Epistemologically, the RTP authors hypothesize that this serves to prime students' expectations. The students, then faced with data from the physical world and their peers' ideas, are then more able to undertake conceptual change.

In physics classrooms, the RTP curriculum has resulted in large degrees of success. On the FMCE, Thornton & Sokoloff (1990) saw normalized gains of over 0.6 for MBL lectures, while students enrolled in non-MBL lectures saw gains of only 0.2. A second version of MBL was developed called Interactive Lecture Demonstrations (ILD; Sokoloff & Thornton, 1997). The ILDs were designed to have many of the same qualities of the MBL, but for use in a lecture hall and only require one computer rather than one for each group. An instructor introduces the phenomenon (e.g., a cart going up a ramp), and demonstrates what it will look like. A student then makes an individual prediction before turning to a partner or two and making a group prediction and discussing the phenomenon. Students are free to change their individual predictions. After a short discussion in class, the teacher then collects data, and the students record the data. The results are projected via an LCD projector, so everyone can see data being collected in real time. The instructor then leads a short conversation and connects the phenomenon to the world at large. The ILD receives reported gains of up to 0.8 on the FMCE, which is much higher than traditional instruction.

Finally, Kozhevnikov and Thornton (2006) report that real-time graphing also tends to increase the visual spatial ability of undergraduate students. The authors point out that spatial ability is an important (and often overlooked) aspect of understanding physics, giving more motivation to adopting MBL strategies. However, as effective as the approach is, other approaches have been taken to bring technology into the classroom.

PI can be differentiated from RTP and ILD style methods by considering what provides a measure of 'authority.' In PI, after the conceptual question is answered individually and discussed in groups, the instructor provides an answer and a short discussion before moving on to the next concept. There is nothing suspect cognitively about this procedure, Harris and Koenig (2006), for instance, describes that students do learn science through 'testimony'. However, Vosniadou and Brewer (1992) show that young students who rely on such testimony may be developing incomplete mental models. The success of PI versus traditional instruction shows that students in PI settings are adopting more scientific viewpoints, so the concern may not be as immediate in older students (who are presumably more capable of formal thought).

RTP and ILD make an effort to let the physical world act as the 'authority' in teaching students. Even though the instructor is present, and responsible for choosing and focusing the content, the data is collected through probes that represent an unbiased picture of the physical world. The student compares a prediction based on an alternative ('non-scientific') framework to probe-collected data designed to focus attention on an unfolding scientific phenomenon. If the prediction does not match data collected through the probe, then the student's cognitive system falls out of balance; there is a disequilibration. While higher gains have been reported on RTP/ILD versus PI, there is far too much noise to compare them directly. The conceptual measures are different (FMCE for RTP/ILD and FCI for PI), and while both groups of researchers report scores with a home-court advantage (they administer the curriculum at the same university the curriculum was developed at), they are still administered at different universities (Tufts University and University of Oregon for RTP/ILD and Harvard University for PI).

IV.3.3 Simulations for learning physics

A relatively new development in science education, especially physics, is that the physical world can be removed from the learning environment. Computers are capable of creating simulated environments, where a selected subset of nature is presented (and potentially warped for learning purposes). While removing the physical world from physics seems curious, simulations give students the opportunities to explore phenomena that are not readily recreated in a lab, or test out universes with different laws of physics.

White (1993) and diSessa (1982) both describe a microworld-based approach. A microworld is a technological environment where only certain physical rules are emphasized, with the effect of training students' attention on certain details. Both White and diSessa's microworlds are used by young middle school students (6th grade), which make the children much younger than those traditionally approaching the abstractions of Newtonian mechanics. However, the students do meet qualitative success in both instances. I will emphasize White's work. DiSessa's approach to microworlds in science education was pioneering. White's, coming 10 years later, had the benefit of blossoming in the field of science education, especially with regard to inquiry-style instruction.

White's microwords gradually increase in complexity, with the belief that that the students can develop abstractions concerning the physical world. She discusses four key stages of knowledge acquisition "(a) motivation, (b) learning, (c) abstraction and (d) transfer" (1993, p. 7). Each of these stages has a distinct phase in instruction. White also took the ambitious step of comparing her sixth graders to high school physics students. While the high school students possessed better problem solving skills, the middle school students had a stronger understanding of force and motion concepts.

(Finkelstein et al., 2005) noted that microworld-style environments can augment the physical world in rich ways. Their research environment focused on electric circuits, a topic covered in second semester undergraduate physics. The traditional approach is to use a collection of wires, batteries, and light bulbs, and systematically look at the properties of various types of circuits. Their alternative for instruction was to offer the same materials in an online environment. However, in the technological tool, the wires were 'transparent,' one could see blue spheres traveling through them, representing how an electron might act.

The experimental group in Finkelstein et al.'s research showed higher conceptual gains in understanding circuits than the traditional group. The researchers attributed this to the new representation. Using traditional physical materials, one cannot directly see an electron. The various experiments they undertake infer it's existence, but the object itself is invisible. By creating a stand-in for the electron, the research group makes many of the equations that describe electric circuits more obvious. Epistemologically, through the representation, the students have a method for 'seeing' an otherwise invisible process. Thus technology can be used to represent the physical world, in essence creating a hyper physical reality.

IV.4 Limitations of reform curricula

Reform curricula, particularly interactive instruction, have been very effective in meeting the challenges that have been posed. Mainly, there is evidence that students who form a conceptual understanding of scientific ideas also develop an ability to quantitatively solve problems. Therefore, methods that reinforce students' ability to adopt scientific concepts are highly accepted in the research community.

For the most part, the lessons learned from reform curricula have remained in middle school, high school, and undergraduate classrooms, without migrating to other levels. Metz (1995) points out that Piagetian research seems to preclude abstract reasoning in elementary aged children, though believes that this is a misinterpretation of Piaget's larger point. Piaget describes how people think and come to conclusions, but this does not describe what they can and cannot think about. Metz wants to offer genuine inquiry science to elementary aged children. Per the discussion already framed in the cognitive science discussion, inquiry science is a social tool, and thus not within the scope of Piaget's theory. Metz concludes that viewing scientific abstractions as impossible for young children misses the point. Children's understanding will be enriched through scientific discourse and discovery, even if their understanding of scientific content is at a different level than adult understanding.

Even if elementary school students are capable of engaging and learning though an inquiry science approach, there remains the problem of who will teach it to them. Interactive methods as popular in the PER community have the benefit of being taught by experts in physics, while this luxury is not available in elementary schools. In fact, many elementary school teachers could be labeled as 'science-phobic' (Schoon & Boone, 1998; Tilgner, 1990), though there are exceptions. Therefore, there are examples of bringing inquiry science not to children, but to elementary school science teachers (Zee, Hammer, Bell, Roy, & Peter, 2005). However, there is no evidence established (yet) that these trained teachers bring a more productive pedagogy upon returning to their classroom.

Conclusion

There's an old story in physics lore. Galileo, a founding father to the field, climbs atop the Leaning Tower in Pisa. With him has taken two sacks, one filled with feathers and one filled with bricks. Eagerly looking on, a crowd has convened on the piazza below. Galileo, the showman, calls out, explaining that he is going to let the two sacks go at exactly the same time. He is curious what will happen. The crowd below is dismissive of the eccentric, knowing perfectly well that heavier things fall faster. Galileo, who, if actually pulled this off, must have had one of history's wriest smiles, leans over the edge and lets the sacks tumble to the ground. To the surprise of the onlookers, they strike the ground at the same time. The heavier bricks could not outrace the lighter feathers.

I do not know if this incarnation of Galileo ever really existed, so I call him mythical Galileo. Mythical Galileo's story is one of terrific science teaching; the kind that likely unfolds in anonymous classrooms every day. With the tools set out in this paper, it is possible to describe excellence in teaching, by revisiting the questions I set out to answer.

(1) What is science?

In Mythical Galileo's case, this question is a little reflexive. Galileo was uniquely attuned to a scientific epistemology; after all, he helped create it. Yet good teachers have a firm grip on what science means and what paths scientific knowledge has followed. Because of Galileo's experience, he, like other good teachers, was able to evoke able to evoke a certain 'scientific' belief in his audience. Specifically, he knew that many, if not all, believed that heavier objects fell faster. Specifically confronting these believes allowed Galileo to confront the science that his audience believed in.

Science often comes across as an imposing set of facts, offered for memorization and recall. A more optimistic belief about the nature of science is that of a changing set of facts, constantly subject to debate and revision. However, this still places a huge barrier to entry to scientific discourse, as one must master both the past and present before being welcomed into the scientific conversation. In the Galileo example, science is a sophisticated mental process for creating new knowledge; it is an epistemology. Good science teaching embraces the epistemological nature of science to go along with core scientific ideas. In this specific case, uniform acceleration due to gravity.

(2) What types of epistemological theories are relevant to learning science?

Even though Mythical Galileo didn't have the benefit of constructive or socio-cultural theories of mind, he still demonstrated an uncanny intuition about psychology. He does not, for example, set out to directly refute Aristotle. A presentation on the history of theories of falling objects will not win over his audience. Instead, he demands that his audience confront their current ideas. Contemporary scholars would say that members of the audience bring their conceptual schemata to the fore, a set of ideas that they use to describe the motion of falling objects. When the audience witnesses the sacks strike the ground at the same time, defying their expectations. Now there is new information to assimilate, and the audience is primed to do so. The equilibration between assimilation and accommodation is broken, and the learners are started along the track to the new scientific conception. Further, while Mythical Galileo never imagined a dynamic system, he knew that his audience's knowledge was stable in the 'heavy-falls-faster' meme, and that this stability must be rattled.

Mythical Galileo didn't have to face many of the questions demanded by socio-cultural theory, as 16th Century Pisa is rather homogeneous. Even still, he manages to get many of the details right. He doesn't get bogged down in esoteric examples. He could, for example, borrow from that sci-fi writer Leonardo daVinci, a contemporary and compatriot, and ask questions about flying machines falling to the ground. If he did, he would lose his audience without the imagination or patience to consider a world of flying machines with no direct relevance to everyday life. Instead, he presented a straightforward situation with everyday materials. Because his material was accessible and unbiased, his entire audience could connect, meaning that his knowledge was completely open.

(3) What pedagogies have worked in teaching science

In the case of Mythical Galileo, this is a redundant question. His pedagogy works. It has much in common with the various styles of constructive pedagogies, as his audience was brought to construct a new understanding. Mythical Galileo was particularly clever in that he did not try to take the mantle of authority for himself. He developed an experiment designed to challenge an existing conception and pave the way to a scientific alternative. The physical world, and the laws that govern it, were given authority.

That said, we shouldn't think that Mythical Galileo's teaching techniques are the only ones that would work. For example, Mythical Galileo didn't adopt any peer instruction technique, other that the dull murmur that accompanied his seeming eccentricity. However, in contemporary classrooms, we know that this is an incredibly powerful technique. Mythical Galileo did start upon the path of guided inquiry. He implied a question, even if it was never explicit. However, he didn't let his audience generate their own questions, which in some cases can be more powerful. Still, an open-ended inquiry would have been outside of Mythical Galileo's goals, so we cannot indict him too harshly (there's a Catholic Church to take care of that).

I left out one of my questions, (4) why study science education? This question was so important to me that I opened the paper with it. Yet for Mythical Galileo, it is an afterthought. I attacked the problem from the point of view of what value science brings society. But to Galileo, both mythical and real, science was practiced out of sheer joy of discovery. This is the ultimate motivation to study science, but we all don't share Galileo's enthusiasm.

Rather, the value of science education can be found in a political revolution that occurred after Galileo's death. In the 18th Century, a radical idea swept into political thinking where individuals were given the right of self-governance. However, with this right, there became the responsibility to make informed decisions about the government. A scientific epistemology is a powerful tool for creating knowledge and building ideas that go into government. This has not diminished. Science is an indispensable tool for thought, and science education of the highest quality benefits all.

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