

CHALLENGING TRADITIONAL ASSUMPTIONS OF HIGH SCHOOL SCIENCE THROUGH THE
PHYSICS AND EVERYDAY THINKING CURRICULUM™

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A thesis submitted to the
Faculty of the Graduate School of the
University of Colorado Boulder in partial fulfillment
of the requirement for the degree of
Doctor of Philosophy
School of Education

2013

This thesis entitled:
Challenging Traditional Assumptions of High School Science through the
Physics and Everyday Thinking Curriculum™
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April 10, 2013

The final copy of this thesis has been examined by the signatories, and we
find that both the content and the form meet acceptable presentation
standards of scholarly work in the above mentioned discipline.

IRB Protocol: 0110.55

ABSTRACT

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Challenging Traditional Assumptions of High School Science through the
Physics and Everyday Thinking Curriculum™

Thesis directed by Associate Professor Valerie K. Otero

Science education in the U.S. has failed for over a century to bring the experience of scientific induction to classrooms, from elementary science to undergraduate courses. The achievement of American students on international comparisons of science proficiency is unacceptable, and the disparities between groups underrepresented in STEM and others are large and resistant to reform efforts. This study investigated the enactment of a physics curriculum designed upon the inductive method in a high school serving mostly students from groups underrepresented in science. The Physics and Everyday Thinking™ curriculum was designed to model the central practices of science and to provide opportunities for students to both extract general principles of physics and to develop scientific models from laboratory evidence. The findings of this study suggest that scientific induction is not only a process that is well within the capacity of high school students, but they enjoy it as well. Students that engaged in the central practices of science through the inductive method reported a new sense of agency and control in their learning. These findings suggest that modeling the pedagogy of the science classroom upon the epistemology of science can result in a mode of learning that can lead to positive identification with physics and the development of scientific literacy.

This thesis is dedicated to all students past who might have felt
the spirit of science if they were ever given a chance.

ACKNOWLEDGEMENTS

I wish to convey my sincerest gratitude to Shelly Belleau for opening her classroom and her practice to me and, through her unparalleled excellence, inspiring me to never give up on our cause.

I also thank the National Science Foundation Grant ESI-0096856 for their generous support of this work.

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CHAPTER 1

INTRODUCTION

In the mystical, fatalistic ages which preceded, electricity was simply an agent of inscrutable Providence. It was Elijah's fire from heaven which consumed the enemies of Jehovah. It was Jove's thunderbolt hurled by an angry God, and it was as presumptuous to study this direct manifestation of God's power in the world as it was for a child to investigate the strap with which it was being punished, or the mental attributes of the father who was behind the strap; and it was only one hundred and fifty years ago that Franklin sent up his kite and found these awful thunderbolts identical with the harmless sparks which he could draw on a winter's night from his cat's back. ...but note that what Jove lost in dignity and power and responsibility through this event man gained (Millikan, 1915, p. 611).

Research in education and related fields have produced a large and compelling body of research on the subject of access to quality schooling. These findings indicate that large disparities in access and outcomes persist despite efforts to address what has come to be called the “achievement gap” (Lee, 2001; Lee & Lukyx, 2005; Marx and Harris, 2006; NRC, 2007b; NCES, 2011; NCES, 2009). These disparities are notable in all examined areas of education, and science education is no exception. Not only do African Americans, Latinos, and Native Americans lag behind their White and Asian peers with respect to performance on large scale measures of science proficiency, these groups are underrepresented in all levels of post-secondary science education and in science, technology, engineering, and mathematics (STEM) careers (NRC, 2007a; NRC, 2011; NCES, 2011; NCES, 2009).

In 2007, groups underrepresented in science careers made up 39% of K-12 public school enrollment, yet only comprised 26% of enrollment in undergraduate studies. Worse, only 18% of STEM bachelor's degrees were awarded to persons from underrepresented groups, and 15% of master's degrees and 5% of doctorates in STEM disciplines were obtained by underrepresented students (NRC, 2011). One may view these findings as *the* dire problem in need of redress. However, they are merely symptoms of a

complex and enduring failure of our science education enterprise to serve large portions of our student population.

Calls to address these glaring failures have been framed in a variety of ways. Policy documents, such as *Rising Above a Gathering Storm* (NRC, 2007b) and *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads* (NRC, 2007a) refer to our nation's youth as human capital necessary for our collective economic competitiveness and success. Such characterizations of the problem tend to focus on the need to maximize human resources and talent in order to compete globally for resources and innovation. These documents point to changing demographic and academic achievement data to stress that untapped potential for driving economic success resides within our underrepresented populations.

Other authors take a more civic-minded approach, implying that the essential ingredients of a functional and fair democracy are informed and intellectually able citizens. The NRC's new Frameworks for K-12 Science Education (2012) stress that in an increasingly complex world of scientific and technological innovation and information, scientific literacy is a vital set of knowledge and skills.

Promoting scientific literacy among all of the nation's people is a democratic ideal worthy of focused attention, significant resources, and continuing effort... America's children face a complex world in which participation in the spheres of life — personal, social, civic, economic, political — require deeper knowledge of science and engineering among all members of society. Such issues as human health, environmental conservation, transportation, food production and safety, and energy production and consumption require fluency with the core concepts and practices of science and engineering (NRC, 2012, p. 11-1).

At least implied in democratically framed calls for increased scientific literacy are the notions that the individual and collective well-being of all citizens is a priority and that all persons have inherent value beyond their role as a source of economic capital. Indeed, there are those of us that assert that the success of our nation must be measured not by the high water mark of those who hold the greatest social and economic standing, but by the opportunities for a high quality of life and social mobility enjoyed by those who are least endowed.

Among the factors that may impact social mobility is access to quality education. And, in a world of ever increasing volume and complexity of scientific and technical tools and information, access to quality science education is at least as equally important as access in any other knowledge domain. Just as Bob Moses (2001) asserts that mathematical literacy is a civil right, I assert that scientific literacy is a 21st Century *human* right. We cannot expect people to lead healthy, productive lives in which they make informed personal and collective decisions without a requisite understanding of the nature of the science and an associated familiarity with scientific principles and theories. Climate change skepticism, the proliferation of bogus health-related products, and the advocacy of intelligent design as topic to be taught in K-12 science courses are striking examples of social phenomena that rely on a lack of scientific literacy among our citizenry.

As stated above, the data comparing the academic performance and representation in STEM careers of underserved groups to those of Whites and Asians reveal disturbing outcomes and trends. Just as the progressive establishment has historically been concerned for the civil rights of all of all members of society, we must continue this cause wherever we find inequitable systems and outcomes. Science and its disciplines have been marginalized to a disturbing degree within public education as accountability legislation has drawn attention and resources to performance gaps in reading, writing, and math (Lee, 2001; Lee & Luky, 2005; Marx and Harris, 2006). Science instruction at the elementary level is perhaps hardest hit by a loss of dedicated instructional time, and schools that struggle the most under the pressures of accountability legislation and standardized testing, those in poor, underserved communities, are most likely to be impacted (Marx and Harris, 2006). Science educators must devise thoughtful ways of overcoming the damaging effects of these short-sighted, misguided measures as these threaten to perpetuate and exacerbate long-standing discrepancies in who receives high quality science curricula and instruction.

Efforts to improve science education in the U.S. are documented as far back as the late 1800's. The "inquiry" movement of last two decades to transform K-12 science learning to more accurately reflect scientific practice is simply the modern version of a movement that has strived to improve science learning

for over a century. Scientists that are perhaps better known for their accomplishments in experimental physics, such as Edwin Hall (1897) and Robert Millikan (1914), struggled in the late 19th and early 20th centuries to bring the practices of science to K-16 physics classrooms. Their efforts were complemented by the other scientists, science educators, and educational philosophers, namely John Dewey (1910), C. Riborg Mann (1912), and Robert Woodhull (1918). Though these scientists and science educators did not always agree on what exactly should be done in the classroom, it is sufficient to say that they all felt the experiences of students and the outcomes of science education to be lacking. One thing upon which they did agree was that somehow the pedagogy and practices that had become routine in science classrooms failed to capture and convey the essence and spirit of science.

The spirit of physics is not composed of Newton's Laws of motion, Boyle's law, *et al.*; and this spirit cannot be imparted to pupils by imposing on them these ideas, arranged in a logical system, to be learned by fair means or foul. The spirit of physics is the intuition of universal relatedness, which the pupils already have; and the function of physics teaching is to assist them in making that intuition concrete and in proving its validity. It took physics three hundred years to do this, and we must not expect the pupils to do so in twenty minutes (Mann, 1912, p. 216).

Despite the efforts of these science education reformers, the spirit of science remains largely absent in our physics classrooms. The U.S. has witnessed many events that have motivated a renewed focus on science education, from the Industrial Revolution to World Wars to Sputnik and the threat of nuclear annihilation. Each of these events has breathed new life and urgency into the notion that our systems of science education were falling far short of their potential.

Sadly, the calls for reform from over a century ago are as applicable today as ever, and we continue to fail to bring the experience of science to our students. The authors of the NRC's *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* summarize the failure of the modern "inquiry" movement.

Similarly, because the term “inquiry,” extensively referred to in previous standards documents, has been interpreted over time in many different ways throughout the science education community, part of our intent in articulating the practices in Dimension 1 is to better specify what is meant by inquiry in science and the range of cognitive, social, and physical practices that it requires. As in all inquiry-based approaches to science teaching, our expectation is that students will themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves (NRC, 2012).

Thus, the call for providing contexts through which students may *experience* science continues. Much of what occurs in science schooling in the U.S. today, as I will demonstrate, presents a misrepresentation of what science is to students and future science teachers. It is important to be clear, as the above quote from the NRC suggests, what is meant when one says students should *experience* science.

The scientific disciplines are unique in that they are founded upon an evidence-based approach to understanding the natural world. More specifically, *the* central practice of science, as described as far back as the 1600’s (Bacon, 1878) and later by the likes of Dewey (1910), Mann (1914), and Millikan (1915), is the *inductive method*. Also called *scientific induction*, it is the process of moving inferentially from specific, concrete observations of natural phenomena to abstract, generally applicable principles.

Scientific practices have appeared in policy documents as descriptive lists in which scientific induction is typically reduced to the development of explanations and models from evidence (AAAS, 1993; NRC, 1996, 2000, 2012). Though accurate, I believe that these descriptions fail to capture what physicists such as Mann and Millikan referred to as “the spirit of science”; that the joy and empowerment of doing science is realized through induction—the process of discovering for oneself the principles that govern the natural world.

The essence of the scientific spirit is an emotional state, an attitude toward life and nature, a great instinctive and intuitive faith. It is because scientists believe in their hearts that the world is a harmonious and well-coordinated organism, and that it is possible for them to find harmony and coordination, if only they work hard enough and honestly enough and patiently enough, that they achieve their truly great results (Mann, 1914, p. 518-519).

These scientists and science educators believed science to be not just a process, but a disposition and a way of approaching the human experience.

Very few physics curricula are developed on the inductive method, but some do exist. The motivation for this study originated on a visit to a local high school teacher's physics classroom. As a novice teacher with a background in biochemistry, she was tasked by her administration to teach physics. Her school did not provide her a curriculum to teach with, and with the help of a colleague she obtained and began to teach the Physics and Everyday Thinking™ curriculum, or PET (Goldberg, Robinson, & Otero, 2007). When I visited her classroom in her second year of using PET, I was incredibly impressed with the level of engagement and discourse. I spoke with the teacher and found that she had great enthusiasm for the curriculum, and remarked that her teaching had been transformed by it.

The NSF funded PET curriculum was developed and tested over several years, and has been heavily researched (e.g., Belleau & Otero, 2012; Goldberg, Otero, & Robinson, 2010; Otero & Gray, 2008; Ross & Otero, 2012), yet few studies have investigated its impact on student affect or on its effectiveness at broadening access to physics for groups underrepresented in STEM. PET was developed by scientists and science educators to model the central practices of science, or the inductive method, and was designed specifically to help students develop an understanding of the nature of science while learning physics. Thus, with the knowledge that this teacher and her students, largely from groups underrepresented in STEM, were having very positive experiences with PET, its enactment in an underserved high school became the focus of this study.

This study investigates the effectiveness of the PET curriculum at increasing access to science for groups underserved by, and therefore underrepresented in science by addressing the following questions:

- What practices are valued among students in a classroom modeled on scientific induction?
- How do students engage in scientific discourse and practices through the PET curriculum?
- In what ways do the structures and enacted practices of the PET curriculum encourage students from historically underperforming groups toward greater participation in classroom activities?
- In what ways do students' participation in scientific practices via PET and students' development of scientific identities mediate one another?

CHAPTER 2

LITERATURE REVIEW

As stated in the previous chapter, science education in America is in crisis. By conventional measures of science proficiency, the performance of students in the U.S. is unacceptable, and the proportion of students choosing and staying on the path to STEM careers is quite small (Neuschatz, McFarling, & White, 2008; NCES, 2006; NRC, 2008). Worse, these problems appear to be even greater for those groups underrepresented in STEM (Lee, 2001; NCES, 2011; NCES, 2009). Recent work concerned with equity in STEM education focuses on expanded notions of what it means to learn science (Barton, 1998; Buxton, 2010; Buxton 2006; Lee and Frad, 1998) or on using the products of science as or for socio-political action (e.g. Roth & Désautels, 2002; Barton & Tan, 2010). Such work often focuses on the clear need for the development of scientific identities among youth from groups underrepresented in science. Though these studies make valuable contributions to aspects of our understanding of science learning, particularly in underserved communities, my study takes a different approach by engaging students in the central practices of science as the mechanism for empowerment. Rather than focusing on student engagement with science as consumers of the products of science, this study was developed upon the hypothesis that student engagement in the development of scientific principles from evidence can be a mechanism for the development of scientific literacy and the empowerment such literacy entails. Through my work I hope to add constructively to this valuable dialogue and to argue that the science itself is not the marginalizing factor in American schooling. In this thesis, I argue that the marginalizing factor is the way science is traditionally MIS-represented in schools. Before discussing what I mean by *school science*, it is necessary to explain what I mean by *science*.

Scientific Induction

The origins of the scientific approach to understanding the natural world can be traced at least as far back as the late 1500's, when Galilei, Kepler, and Bacon rejected the Aristotelian approach of creating

a priori principles from thought and logical argument to explain the natural world. These early scientists rejected a dogmatic approach to explaining the natural world for a method based on observable evidence. Bacon used the term “induction” in 1620 in his book *Novum Organum* (1878) to describe what he believed to be a superior approach to understanding the natural world.

Hence, the need of a new method of Induction, which shall not merely accumulate but select instances on certain rational principles, draw legitimate inferences from them, and thus guarantee the truth of those first principles from which our deductive reasoning proceeds. This more scientific form of Induction it is more especially the aim of the *Novum Organum* to supply, but, previously to laying down any rules for it or exemplifying its employment, it is necessary to insist on its importance, to free the mind from those obstacles which might prevent it from having recourse to this assistance, to point out the sources of our errors in the past, and to shew what hopes may be conceived of the future (Bacon, 1878, p. 5).

The scientific approach is at its core the *inductive method*, in which many concrete observations of some natural phenomenon are made in order to inferentially develop an abstract, generally applicable principle. The inductive method is the very model of the ideal learning process promoted and described by educational psychologist and activist, John Dewey (1910) and espoused by early 20th Century scientists and science educators (e.g., Mann, 1912; Millikan, 1909; Woodhull, 1918). Kuhn (1977) used the term “scientific revolution” to describe those examples of scientific induction that have changed the very frameworks through which we observe and model the natural world. As Kuhn notes, the majority of scientific work is actually deductive or “normal science,” yet it is the inductive method that distinguishes the sciences from all other disciplines. Scientific induction entails not only developing evidence-based models and theories, but also requires social consensus. A scientific explanation must be subject to the scrutiny of the scientific community, and, if applicable, replicated in order to take its place as the currently accepted theory.

Scientific communities make meaning using a unique synthesis of linguistic, mathematical, and visual-representational tools (Lemke, 2001). A consideration of how students use and learn to use the tools

of science in the physics classroom must take into account the processes by which students come to engage in these practices. Brown, Collins, and Duguid (1989) explain the social and cultural nature of tool use:

Learning how to use a tool involves far more than can be accounted for in any set of explicit rules.

The occasions and conditions for use arise directly out of the context of activities of each community that uses the tool, framed by the way members of that community see the world. The community and its viewpoint, quite as much as the tool itself, determine how a tool is used (Brown, et al., 1989, p. 33)

In other words, a tool and its usage can only be fully understood in the sense that it is used in a manner that is recognized and accepted within the community that values its use. A community is at least in part defined by its use of tools, and the use of a tool goes beyond facilitating the accomplishment of some task or goal. The tool itself, be it a form of language, a means of representation, or a particle collider, fundamentally changes the nature of the activity in which it is used.

The scientific community is defined by particular discourse practices and tool use (Otero, 2004a, 2004b). Shared understandings of tool usage such as symbols (e.g. the letter “v” represents the speed of an object, whereas a bold “**v**” or a v with an arrow over it denote a parameter representing both speed and direction) or particularities of discourse such as sentence construction around particular terminology (e.g. an object does not *give* or *receive* a force, rather an object *exerts* or is *acted upon* by a force) distinguish the scientific community. Likewise, the use of data to support claims, the construction and application of models, and the use of mathematical tools are examples of tool usage central to scientific practice.

The term *scientific induction* is intended here to encapsulate the scientific practices of developing new understanding about the natural world. These include posing questions, arguing with evidence, constructing or utilizing scientific models, reasoning mechanistically, and reasoning inductively to extract generally applicable principles. Perhaps the most subtle and one of the most important aspects of science is the distinction between observation and inference and the understanding that no claim is ever proven. Rather, it may only be accepted based on both a preponderance of evidence and peer consensus and is always subject to revision in light of new evidence. Thus, the idea of a “fact” has no place in scientific discourse. And though no claim may ever be proven, hypotheses may be falsified, meaning that it is

determined to be unacceptable based on the evidence available. I use the term *scientific literacy* to describe the requisite ability to engage in scientific discourse and practices with an understanding of the nature of scientific knowledge production. This form of “literacy” may be applied to (or assumed for) official members of the scientific community as well as others outside of the scientific enterprise that may engage in these practices.

School Science

The question of what practices are most common in school science lies at the heart of our attempts to understand and address the science achievement gap. Do the dominant modes of science schooling encourage practices that meet the needs of students from all groups and classes? Given the current state of STEM participation and achievement in the U.S., one can safely assume that the answer to this question is a resounding “no” for large proportions of students. An examination of the central practices of school science may offer insight into the extent to which the dominant modes of participation in science classrooms are relevant to the central practices of science.

Researchers have examined the nature of classroom activity in schools in general and in science classrooms specifically (Bloome, Puro, & Theodorou, 1989; Jimenez-Aleixandre, Rodriguez, & Duschl, 2000; Lemke, 1990; Pope, 2002). Pope (2002) investigated academic success in a high school setting and found that “doing school,” that is, engaging in practices that lead to positive recognition in school, often have little to do with academic achievement. Pope found that the dominant practices occurring in schools often had more to do with students employing strategies to obtain high grades and garner a perception of their academic proficiency than developing intellectual capacity or subject matter knowledge.

Jimenez-Aleixandre, et al. (2000) applied the idea of “doing school” in their examination scientific argumentation skills in a science classroom. They found that “doing school” was common in the science classroom and contrasted meaningful learning that results in domain specific understanding with something called *procedural displays*. Procedural displays are an aspect of “doing school” in which both

students and teachers performed practices that are valued in the school context but have little relation to scientific practice.

Examples of procedural displays in the science classroom include calculating the standard error for every measurement made in the laboratory without considering the causes or implications of the errors or producing graphical representations of data whether or not it is meaningful or appropriate to the broader

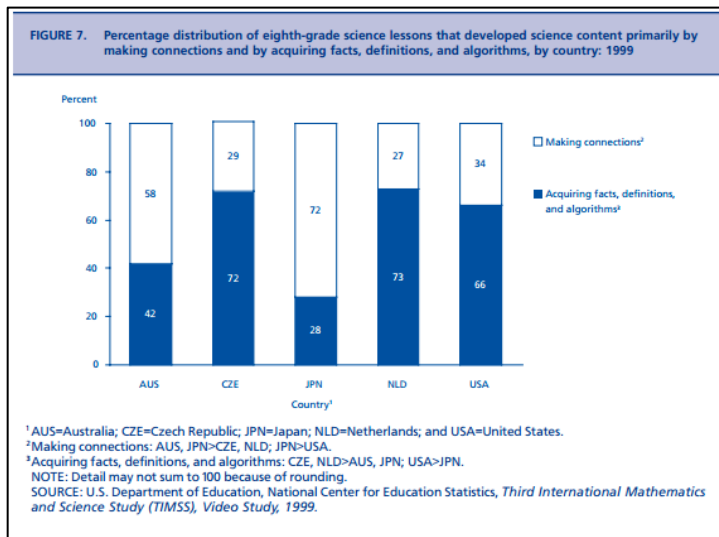


Figure 2.1. TIMMS results.

“doing school” are more likely the norm than not. Among the findings, the majority of science lessons observed in the U.S. did not engage students in the central practices of science, as shown in Figures 2.1 and 2.2. The majority of science lessons observed involved the alleged acquisition of facts, definitions, and algorithms, rather than participation in scientific inquiries into natural phenomena.

task within which they occur. Thus, the phenomenon of “doing school” appears to be an artifact of the culture of schooling and to have little to do with scientific practice.

An examination of the most recent TIMMS study of science instruction in several industrialized countries (2006) reveals that the findings above related to

TABLE 3. Percentage of eighth-grade science lessons in which students engaged in different inquiry activities before, during, and after independent practical work, by country: 1999

Student activity	Australia (AUS)	Czech Republic (CZE)	Japan (JPN)	Netherlands (NLD)	United States (USA)
Generated the research question ¹	3!	‡	‡	‡	‡
Designed procedures for investigations ²	10	‡	5!	‡	5
Made predictions ³	11	‡	23	41	8
Interpreted the data or phenomena ⁴	56	20	43	24	33
Collected and recorded data ⁵	62	8	59	29	31
Organized or manipulated data collected independently ⁶	9	‡	‡	8	8
Organized or manipulated collected data guided by teacher or textbook ⁷	27	3!	37	8	19

‡ Reporting standards not met. Too few cases to be reported.
 ! Interpret data with caution. Estimate is unstable.
¹ Generated the research question: No measurable differences detected.
² Designed procedures for investigations: No measurable differences detected.
³ Made predictions: JPN>NLD.
⁴ Interpreted the data or phenomena: AUS>CZE, NLD; JPN>CZE.
⁵ Collected and recorded data: AUS, JPN, NLD, USA>CZE; AUS, JPN>NLD, USA.
⁶ Organized or manipulated data collected independently: No measurable differences detected.
⁷ Organized or manipulated collected data guided by the teacher or the textbook: AUS, JPN>CZE, NLD; USA>CZE.
 NOTE: Totals for students organized or manipulated data on their own or under the direction of the teacher or textbook do not sum to students collected and recorded data because students do not always manipulate collected data.
 SOURCE: U.S. Department of Education, National Center for Education Statistics, *Third International Mathematics and Science Study, Video Study, 1999*.

Figure 2.2. More TIMMS results.

Table 2.1. The Practices of Science Schooling versus Practices of Science.

<u>Practices of Science Schooling</u>		<u>Value Practices of Science</u>
Engaging the canon of scientific knowledge by reading about and answering questions	≠	Engaging the canon of scientific knowledge by investigating phenomena in the natural world
The right answer is sanctioned solely by the teacher and the textbook	≠	The right answer is sanctioned by a preponderance of evidence and community consensus
Analyzing and interpreting data to answer computational or conceptual questions	≠	Analyzing and interpreting data to test hypotheses and construct explanations
Utilizing established models as facts with which to answer questions	≠	Developing models, principles, and theories from evidence and applying them to generate explanations
Well established norms and procedures for behavior	~	Well established norms and procedures for collecting and reporting data
Recapitulating conceptual explanations to answer someone else's questions	≠	Constructing evidence-based explanations to answer own questions
Engaging in particular discourse patterns (sentence construction, vocabulary, etc.)	=	Engaging in particular discourse patterns (sentence construction, vocabulary, and symbol use, etc.)
Wrong answers are not valued.	≠	Wrong answers are valued (i.e. falsification)
Seeking acceptance and approval from the teacher	≠	Seeking satisfaction that an explanatory model is reached

These results are disturbing, yet it is not surprising that the cycle of instruction that misrepresents science is a difficult one to break out of. As a science teacher myself, I reproduced the only thing that I knew, a mostly didactic attempt to distribute science as already abstracted and generalized models, theories, and principles to be acquired by students, mixed with some labs designed to confirm these principles. The TIMMS results (2006) strongly suggest that this type of science teaching practice is all too common. A comparison of the central practices of science schooling and the central practices of science is shown in Table 2.1. Though this comparison is not intended to be exhaustive, an examination of Table 2.1 reveals a disturbing lack of coherence between the valued practices of science schooling and those of the scientific community. So, how is that this traditional misrepresentation of science has become the status quo in our schools? A consideration of the three sectors of science teacher preparation—undergraduate science courses, teacher education, and K-12 schools—reveals, just as the TIMMS study has, that this mode is prevalent in undergraduate courses as well as K-12 schools (Achieve, 2013). Teacher preparation

programs, on the other hand, have espoused an “inquiry” approach to science learning, yet no one can seem to agree on what that term actually means, especially as it relates to scientific practice. The authors of the NRC’s *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* attest to this problem.

Similarly, because the term “inquiry,” extensively referred to in previous standards documents, has been interpreted over time in many different ways throughout the science education community, part of our intent in articulating the practices in Dimension 1 is to better specify what is meant by inquiry in science and the range of cognitive, social, and physical practices that it requires. As in all inquiry-based approaches to science teaching, our expectation is that students will themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves (NRC, 2012, p. 30).

Statements such as the NRC’s above and other research (Ross, et al 2011; Wallace & Kang, 2004; Windschitl, 2004) suggest that science teacher educators may lack a requisite understanding of scientific practice and thus do not provide adequate teacher preparation experiences for future science teachers. The research presented above about what actually happens in K-12 science classroom supports such a conclusion.

Given that the three sectors of science teacher preparation engage students in practices that are at best a small subset of the practices that scientists engage in their work, it follows that our high school and college graduates and science teachers have most likely never participated in the central practices of science. A consideration of the literature assessing what is valued in school science as compared to scientific practice (Bloome, et al, 1989; Jimenez-Aleixandre, et al., 2000; Lemke, 1990; NCES, 2006) leads us to the inevitable conclusion that students are directed to engage in practices that are specific to schooling and have little authentic connection to scientific practices. As our future science teachers engage K-12, undergraduate, and teacher preparation curricula and instruction that misrepresents science, it should be in no way surprising to find that many science teachers may, in fact, be lacking scientific literacy (Ross, et al 2011; Wallace & Kang, 2004; Windschitl, 2004).

Still, the question of disparate outcomes among racial and ethnic groups remains unexplained in this comparison of the practices of science to those of school science. An understanding of what leads to disparities in school science is necessary if we are to seek solutions to racial performance and participation gaps.

Critical Theory

Critical frameworks offer a means to understand the historical and social dynamics that manifest as privilege for some and marginalization for others. They further offer the means to question the status quo social relations and outcomes in greater U.S. society. Critical race theory (or CRT) was developed by legal scholars and elaborated by education researchers to develop theoretical frameworks for understanding disparities in society in general and, more specifically, as they manifest in schools (Bell, 1980; Ladson-Billings & Tate, 1995). These frameworks often focus on the constructs of *privilege* and *marginalization*. *Dominant* groups, or those who exercise relatively high levels of control over economic and social resources, tend to be *privileged* as compared to those from non-dominant groups. Those from non-dominant groups, by definition, have more limited access to economic and social resources, and tend to operate from less powerful, at best, or more likely *marginalized*, positions in society. These relations are influenced, at least in part, by the fact that those from non-dominant groups are not socialized into the practices of the dominant culture and therefore operate at a disadvantage (Eckert, 1989; Lareau, 2003; Willis, 1977). Further, non-dominant groups are distinguished not only by lower socio-economic status, but also by race or ethnic categorization.

It should be made clear that alignment with this perspective implies an ideological position on issues of equity and access in American society. This perspective assumes that aspects of American society historically advantage some groups over others and that this system of relations is morally unacceptable. In this research, I am utilizing a framework informed by this perspective and acknowledge the inherent bias that such a lens entails.

Ladson-Billings and Tate (1995) have theorized the construct of race in American schooling and developed three propositions upon which this critical race theory of education rests: (1) race continues to be significant in the United States, (2) U.S. society is based on property rights rather than human rights, and (3) the intersection of race and property creates an analytic tool for understanding inequity. Regarding proposition one, the fact that race is a factor in schooling can be seen in overwhelmingly conclusive statistical data representing stark disparities in graduation rates and achievement in various subject matter on a range of standardized tests (Lee, 2001; NRC, 2007; NCES, 2011; NCES, 2009). As to proposition two, poverty is strongly correlated with, and is perhaps the single best predictor of, academic under-performance (Sirin, 2005). Among the varied ways that property plays a significant role in race and power relations in U.S. schools is the issue of curriculum as property and the privileged access that some groups have to quality curricula and instruction. Regarding proposition three, tracking, inequitable school funding, and ideological beliefs and values of teachers as related to race are three ways that access to curriculum can vary with race (Bartolome, 2004; Gilbert and Yerrick, 2001). Because privilege tends to benefit those from the dominant racial and socioeconomic groups, race must be considered as a potential factor in social power relations, access to resources, and ultimately of the quality of classroom learning in U.S. schools where the vast majority of teachers are from suburban, middle class communities.

Cultural positioning in American schooling, and more specifically the positioning associated with race, has been examined using critical race theory. DeCuir and Dixson (2004) investigated the experiences of African American students at an elite, predominantly White high school in the Southeast. Combining the work of earlier theorists (Bell, 1980; Ladson-Billings & Tate, 1995), DeCuir and Dixson proposed the following tenets of CRT: (1) Whiteness as property, (2) the permanence of racism, (3) interest convergence, (4) the critique of liberalism, and (5) counter-storytelling. The authors employed CRT to examine the ways that racism operated to silence and marginalize the few African American students attending a nearly all White school and found that racism continued to negatively affect the experiences of African American students. Both the explicitly racist acts of students and more subtle racism exhibited by faculty and students made African American students feel that this racism had significant detrimental

effects on their educational experience. The tenets of CRT employed in their study share much in common with the three propositions of Ladson-Billings and Tate above but add two key aspects to that framework, *interest convergence* and *the critique of liberalism*. Interest convergence is a useful analytic tool that can explain changes that benefit marginalized groups as simultaneously satisfying aims of the dominant group or, at least, not considerably disrupting the status quo. For example, Bell (1980) argues that the landmark Supreme Court decision *Brown vs. Board of Education* is an example of interest convergence in that the actual gains of African Americans following this decision have been minimal, thus this legal decision has done little to disrupt the status quo. School closings in Black communities, the dismissal of scores of Black teachers and administrators, and tracking and lack of access to quality curriculum and instruction are cited by Bell as evidence that the plight of Blacks to achieve comparable educational opportunities was minimal in spite of the Supreme Court's ruling.

The critique of liberalism is described as a triad of notions embraced by liberal legal ideology: colorblindness, neutrality of law, and incremental change (Decuir and Dixson, 2004). These notions, they assert, may be appealing in the abstract, but the reality is that the concepts of colorblindness and neutral law are fantasies that neither reflect the reality of race relations nor any attainable system of relations in our society. The idea of incremental change represents the notion that changes in the existing social order are difficult to achieve, and the expectation is that such changes come about slowly and in small increments. CRT scholars assert that, in light of the proliferation and magnitude of the injustices in our society, appeals to less disruptive, incremental changes are unacceptable and are simply a strategy to maintain the status quo. The tenet of counter-storytelling is also added in the description of CRT offered by Decuir and Dixson (2004). They assert that the voices of the oppressed are rarely heard and, given the history of racism and oppression in the U.S., the dominant narrative must be challenged.

Although one may argue that race is perhaps the most significant feature in the examination and explanation of inequity and oppression in the U.S., a critical approach with a focus solely on race will necessarily overlook other extremely important factors and how they interact with each other. As Crotty (1998, p. 158, paraphrasing Kincheloe and Maclaren, 1994, p. 139-40) points out in his description of the

basic assumptions of critical theories, “oppression has many faces, and concern for only one form of oppression at the expense of others can be counter-productive because of the connections between them.” The intersections of race with other factors such as gender, socioeconomic status, or sexuality must not be overlooked if we are to understand the nature of oppression and the social constructs that mediate social relations. Ladson-Billings and Tate also address this issue by considering the intersections of race and other prominent demographics.

Although both class and gender do intersect race, as stand alone variables, they do not explain all of the educational achievement differences apparent between whites and students of color. Indeed, there is some evidence to suggest that even when we hold constant for class, middle-class African American students do not achieve at the same level as their white counterparts (Oakes, 1985).

Although Oakes reports that “in academic tracking...poor and minority students are most likely to be placed at the lowest levels of the schools sorting system” (p. 67), we are less clear as to which factor—race or class—is causal. Perhaps the larger question of the impact of race on social class is the more relevant one (Ladson-Billings & Tate, 1995, p. 51).

It may be sufficient to say that race and class are inextricably linked in the U.S., and causal inferences about the impact of one variable relative to the other on achievement are difficult to make. Even if the relative magnitudes of causal factors were isolable, that certainly does not imply a solution for present state of affairs.

This work is also informed by the work of another prominent critical theorist, Paolo Freire. In his seminal work, *Pedagogy of the Oppressed* (1972), Freire draws distinctions that may be applied to the work of critical scholars and activists. Perhaps the most important point that Freire makes for activist researchers who choose to enter the worlds and lives of the marginalized and attempt to change them into something that we believe is better, is that *no person can liberate another*. The fight for true freedom and opportunity must be realized in the struggle of the oppressed, and critical activists can only hope to bring about the conditions that can enable people to seize their right to shape their own futures.

The truth is, however, that the oppressed are not “marginals,” are not people living “outside” society. They have always been inside—inside the structure which made them “beings for others.” The solution is not to integrate them into the structure of oppression, but to transform that structure so they can become “beings for themselves (Freire, 1970, p. 55).

Assuming that others need or even want aspects of the lives of the privileged is a mistake. In my view, the role of the critical activist is to attempt to create the contexts through which the marginalized may realize their own struggle for whatever it is that they deem worthy. In this case, creating contexts for the attainment of scientific literacy and its associated empowerment is the goal.

Critical theory provides a framework through which we may understand the social dynamics of privilege and marginalization in society and as they relate specifically to schooling. School funding and access to quality curriculum and instruction are two very visible ways that race and socioeconomics interact to produce and reproduce the status quo of inequitable access and outcomes in public education.

Whereas critical theories often take a relatively broad approach to understanding social and institutional structures, ethnographers from anthropological traditions often take a more fine-grained approach focusing on social and cultural practices. Scholars have long argued that the social and cultural mismatch of various non-dominant classes and cultures with respect to those who write and implement the curriculum leads directly to the reproduction of social inequities. Willis’ study of class dynamics in British schools demonstrated how the resistance of working class students to the dominant culture resulted in a reproduction of social stratification and inequities (1977). Likewise, Eckert’s work in a suburban Detroit schools highlighted the marked class distinctions that play out in schools, contrasting the experiences of students who conform to and re-create the dominant middle class culture of schools, the *jocks*, with those of students who resist the dominant culture, the *burnouts* (1989). Lareau (2003) took a more home and family-oriented approach to the study and comparison of the practices of working class and poor families to those of middle class families. Drawing on the work of Bordieu and Passeron (1977), Lareau found that different parenting styles associated with class resulted in very different interactions with persons of authority and institutions such as schools. These studies demonstrate how social capital, and the mismatch of social capital among dominant and non-dominant groups, perpetuates class inequities.

Though Willis and Eckert focused on class vis-à-vis the general culture of the schools they studied, Lemke specifically examined the role of cultural positioning in science schooling. He remarks on the interaction of science understanding and social and cultural backgrounds of students:

Of course students do independently construct some kinds of similarities between situations on their own. These may agree with those constructed by the discourses and practices of science or they may not. The odds are not in the students' favor. When students do effectively and more or less independently recapitulate the history of modern European science, it is largely because they are so positioned within contemporary society that they have already begun to construct some of the higher-order patterns that characterize how our dominant cultural tradition approaches certain kinds of problems. This will be much more commonly the case for students of upper-middle class cultural background than for students who are not daily immersed in the dominant subculture of our society, the one that dictates the curriculum. It is not evidence of superior intelligence, but of privileged cultural positioning (Lemke, 1994).

Lemke argues that the phenomenon of cultural positioning leads to disparate learning outcomes, not because of differences in intelligence, but because of social and cultural factors. Lemke argues that because the practices of privileged cultures are closely aligned with the practices found in traditional schooling, it is no way surprising that students from privileged backgrounds are recognized as performing better. Furthermore, it is unclear in the quote above whether Lemke is referring to scientific discourse or the discourse of school science, but given that this research is conducted in schools, we can be reasonably certain that the practices in question are those of school science rather than science.

Marginalized by Science or School?

Critical theory and the phenomenon of cultural positioning provide an explanation of how access to quality curriculum and the mismatch of social and cultural capital between subgroups and the dominant culture of schooling result in disparate outcomes. It is important to note, however, that the culture of science is not implicated in this unacceptable system of relations. It is school science that students experience, and we have established that school science bears little resemblance to science. And though

some may believe science to be the problem and are finding ways to work around or outside of the disciplines of science itself, they are, in fact, reacting to school science instead.

Thus, a critical perspective compels us to examine the dominant practices of science schooling and to consider how these practices privilege some and function to marginalize the very groups we find to be under-represented in STEM fields. A great deal of research has found that, though the most privileged students are recognized as academically successful in science schooling, these same students are found to perform quite poorly regarding evidence-based argumentation and sense-making in science (Abd-El-Khalick, 2000; Hammer, 1994; Lederman, 1999; Windschitl, 2004). So, we find that though the relatively privileged among us do engage in and often excel at the practices of school science, they cannot be said to have participated in the central practices of science.

Not only does the majority of science instruction misrepresent scientific practice, there are theoretical and empirical reasons to believe that traditional instruction hampers or even precludes the kind of sense-making, self-regulation, and full and complete engagement that can be associated with engagement in scientific inquiry. Ames (1992), investigated the relationship between classroom structures and students' orientations toward learning. She characterized a dichotomous system of goals to address the broad issue of student motivation. Ames (1992) called these two contrasting goal orientations *mastery* and *performance* and investigated the relationship of these goals to three classroom structures: tasks, evaluation and recognition, and authority.

Table 2.2. Factors associated with performance and mastery goals.

Performance	Mastery
Ego-involvement; self-worth related to one's perceived ability	Likely to maintain achievement behavior over time
Outcome varies with ability	Outcome varies with effort
Ability is evidenced by doing better than others, surpassing normatively-based standards, or achieving success with little effort.	Effort leads to success and a sense of mastery
Public recognition that one has done better than others is particularly important	Intrinsic value of learning
Learning is viewed only as a way to achieve a desired goal, and attention is directed toward normatively defined success.	Oriented toward developing new skills, improving competence or attaining a sense of mastery based on self-referenced standards
Fosters <i>failure-avoiding</i> behavior and avoidance of challenging tasks	Preference for challenging work and risk-taking
Negative affect follows failure followed by a judgment that one lacks ability	Persistence in the face of difficulty; <i>failure-tolerance</i>

These two contrasting goal orientations are associated with different approaches to learning, differences in how one's sense of self-efficacy and competence are perceived, and ultimately, different attitudes about the purposes of learning, as outlined in Table 2.2. A performance goal is tied strongly to the salience of social comparisons in the learning environment. Central to this goal are one's perceived ability relative to the abilities of others and a sense of self-worth related to these comparisons of ability. The social comparisons associated with a performance orientation result in an inherently normative sense of achievement in learning, as achievement is perceived as performing better than others or with respect to some normative standards.

In contrast, a mastery goal tends to orient learners toward the development of new skills and understanding, improving competence, or achieving a self-referential sense of mastery. Effort is seen as leading to success when success is defined as a sense of competence, rather than being tied to the performance of others. Ames describes implications for these contrasting goal orientations:

Considerable research linking mastery and performance achievement goals to different ways of thinking about oneself and learning activities suggests that a mastery goal elicits a motivational pattern that is associated with a quality of involvement likely to maintain achievement behavior, whereas a performance goal fosters a failure-avoiding pattern of motivation...Mastery goals have also been associated with a preference for challenging work and risk taking, an intrinsic interest in learning activities, and positive attitudes toward learning (Ames, 1992, p. 261).

Of particular note above is the contrast between a mastery orientation, associated with the goals of understanding and marked by a preference for challenge and risk taking, and what is called *failure-avoiding* behavior associated with a performance goal. Speaking from personal experience, much of my own formal physics learning can be characterized as being wrought with pressure to perform and anxiety over the pressure to display competence, both publicly in class and on normatively defined exam performance. For me, this too often resulted in a self-protective mode of failure-avoidance, as contrasted with engagement in tasks with the intent of understanding and achieving a sense of mastery. Further, it is not difficult to find someone who has had an undesirable experience in a physics class, and a sense of one's own inadequate performance relative to others may play a significant role in the negative feelings

associated with physics learning. A study by Redish, Saul, and Steinberg (1998), showed that a large sample of traditional undergraduate physics courses resulted in a negative impact on students' attitudes toward science and science learning. A later study by (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006) replicated these results. Incidentally, the curriculum that is the subject of this study is the only physics curriculum in broad use to show positive effects on students' attitudes (Lindsey, Hsu, Sadaghiani, Taylor, & Cummings, 2012; Otero & Gray, 2008).

Ames considers how classroom structures may influence students' orientations to mastery and performance goals and behavior to classroom. The nature of tasks and the students' sense of control and choice in tasks can affect their orientation toward learning. For example, tasks that are diverse and varied may provide fewer opportunities for students to engage in comparisons of their own ability relative to that of others. Tasks that require individual work followed by publicly shared individual answers contrast with tasks that require collaboration and a publicly shared answer provided by a group. Applying this framework, the individual task invites social comparisons and the collaborative task attempts to minimize them. Ames also considers the construct of authority, also referred to as a teacher's orientation toward student autonomy, with regard to students' orientation toward learning. Greater choice and a sense of personal control encourage a mastery orientation, whereas a teacher's use of external rewards and other controlling behaviors can induce a performance orientation.

Most relevant to this study, Ames considers the effect of classroom evaluation practices on students' orientations toward learning. Specifically, evaluation practices that invite social comparison appear to have a strong effect on students' perceptions of themselves, their peers, and the tasks undertaken in the classroom.

The impact of social comparison on children when they compare unfavorably can be seen in their evaluations of their ability, avoidance of risk taking, use of less effective or superficial learning strategies, and negative affect directed toward the self...In classrooms characterized by frequent grades and public evaluation, students become focused on their ability and the distribution of ability in the classroom group. Many students not only come to believe that they lack ability but this perception becomes shared among peers (Ames, 1998, p. 264).

These findings indicate that evaluation that is frequent and salient invites social comparison and may lead to a performance orientation. Such an environment is likely to have differential effects, depending on the type of recognition one most often receives. It is not hard to imagine that the most detrimental effects would fall upon those students for whom the normatively defined success of the traditional science classroom is elusive or even undesirable. Considering the phenomenon of cultural positioning discussed earlier, it follows that students from non-dominant groups may bear the brunt of the negative effects of such social comparison. Prominent and frequent evaluation is more likely to have negative effects on those students whose cultural backgrounds and social practices are less well aligned with the backgrounds of those who write and administer the curriculum. How then can the learning environment be reorganized such that authoritative evaluation is minimized or replaced by practices that encourage a mastery orientation marked by valuing challenge, risk taking, and positive attitudes toward learning? How do we break out of centuries old, traditional modes of instruction that encourage students to take up a mode of participation marked by self-preservation and failure-avoidance?

More recent research on student motivation attempts to take a more explicit account of contextual variables in understanding student motivation. Whereas the work of Ames (1992) might be considered more classically-oriented in that contextual factors such as social or classroom structures are thought to impact participants in those contexts, a sociocultural perspective takes the participant as an element of, and thus a co-creator of, the social system within which he or she is set. Informed by sociocultural theorists such as Vygotsky (1986), and researchers strongly influenced by Vygotsky such as Werchst (1985) and Lave and Wenger (1991), Mcaslin (2009) and Hickey and Zuiker (2005) present a participatory perspective on student motivation. This perspective is strongly rooted in the idea that learning involves moving from a peripheral status with respect to a community to fuller participation marked by engagement in and greater responsibility for carrying out the central practices of a *community of practice*. This framework, called *legitimate peripheral participation* by Lave and Wenger (1991), represents a view that learning is the movement to fuller participation in a community defined by its central practices, including recognition of occasions for the appropriate use of tools.

Drawing on the work of Greeno (1998), Hickey and Zuiker (2005) present a framework for understanding student motivation called *engaged participation*. In their view, the realization of positive student motivation depends on the extent to which social practices are organized to encourage meaningful engagement in practices of the domain of interest. Further, they assert that identity development and meaningful engagement are linked.

Engaged participation is about negotiating one's identity with different and potentially conflicting communities of practice. Necessarily, this participation involves conformity with and alienation from prevailing standards and values, because *these standards and values are a function of the knowledge communities those practices represent*. This view of engagement involves nonparticipation as much as it involves participation because this model assumes participation in some activities and nonparticipation in others reciprocally defines identity (Hickey & Zuiker, 2005, p. 262).

This view of the reflexive process of identity formation and community participation (and non-participation) and recognition is consistent with critiques of some applications of the *legitimate peripheral participation* framework to classroom settings. As has been noted by both Lave and Wenger (1991) and others (Nespor, 1994; O'Connor & Allen, 2010), the application of the framework of legitimate peripheral participation to other learning contexts, such as formal classroom learning, requires further consideration of the differences between the American classroom community and the small-scale craftwork communities used by Lave and Wenger in the formulation of the perspective. O'Connor and Allen (2010) note that the communities portrayed by Lave and Wenger (1991) were "explicitly benign, in the sense that it was possible, and expected, that all or nearly all apprentices would move toward full participation in the communities and in the broader society." Further, they state that "Many contemporary contexts are, in contrast, decidedly not benign and in fact involve active organizing work, conscious or not, to ensure access to valued futures for only some participants" (pp. 162-163).

Hickey and Zuiker (2005) make the very important point that student identity development occurs as one enacts participation in some practices while rejecting others. In the current model of compulsory schooling, students are in many ways pressured, if not coerced, to participate in ways that may or may not

be aligned with the official and unwritten doctrines of classrooms and schools. Indeed, the nature of this participation depends greatly on the extent to which the central practices of schooling align with the basic emotional needs of students, the need for a sense of self-efficacy, and the need for a sense of connection to the communal practices students are asked to engage in.

As demonstrated above, science schooling and the practices it entails have little to do with the central practices of science. Yet, a consideration of the common practices of science schooling, such as procedural displays (Bloome, et al., 1989), in the context of *mastery* and *performance* orientations toward learning (Ames, 1992) raises important questions about the forms of participation that may be engendered by engagement in these practices. Does engagement in “doing school” (Jimenez-Aleixandre, et al., 2000) and associated submission to the authoritative judgment of one’s ideas by teacher and textbook engender a performance orientation marked by a normative sense self-perception and failure-avoidance? The findings of Ames (1992) suggest that this form of engagement will engender a failure-avoidance mode. If we accept traditional evaluation and sorting mechanisms as the incentive for learning, those whose cultural positioning aligns with the dominant culture will continue to be recognized as successful, while those whose social and cultural repertoires do not will likely be filtered out of the pipeline to scientific literacy and possible interest in STEM careers. The statistics (Lee, 2001; NRC, 2007; NCES, 2011; NCES, 2009) discussed earlier strongly suggest that the public and prominent evaluation of procedural displays that are largely taken as learning in American schools can drive students toward failure-avoidance and performance anxiety and away from engagement in learning in the pursuit of developing a sense of mastery and enjoyment.

The finding that frequent and prominent evaluation invites social comparison and orients students toward a failure-avoidance mode in learning (Ames, 1994) can set one off in search of ways to suppress traditional modes of evaluation. Yet, I argue that we should consider looking to scientific practice if we are to fundamentally redesign evaluation practices in the science classroom. In its ideal sense, science is a set of practices that produces new and tentative understanding via the consideration of evidence and through the building of social consensus that a posited explanation best accounts for all of the available evidence.

This could not be more different from the common practices of school science in which all ideas are subject to the authoritative evaluation of the teacher and text, rendering the spirit of science nonexistent in the classroom and science literacy inaccessible to students. In its current state, science instruction presents fact-based misrepresentations of science and selects a small proportion of students, typically from dominant groups, for success. I hypothesize that if science learning is fundamentally reorganized to model scientific practice, we may realize very different outcomes for our students.

The preeminent place of evidence in the scientific approach stands in stark contrast to the dominant modes of science schooling. The alleged acquisition of facts, definitions, and algorithms, as found in the TIMMS study (2006) discussed above, conveys science as a body of facts, and worse, an authoritative source of knowledge. When students are required to commit scientific “facts” to memory without the means to understand from whence they came or their tentative nature, these “facts” might just as well be the dogma of religious or political doctrine. Thus, scientific literacy requires an understanding, indeed I claim requires an experiencing of, how scientific knowledge is constructed. This understanding, I assert, can only be made possible by learning to use and appreciate the tools of science in order to develop an evidence-based understanding of some natural phenomenon.

It should be made clear that it is not my view that authentic scientific practices are in any way culture free or that they somehow transcend the cultural contexts that give rise to them. Nor do I wish to minimize the record of sexist and racist practices that communities of scientists have engaged in historically. The idealized version of science that I use as a reference to compare school science to is not intended to represent science in practice as ideal and egalitarian. Rather, it is the epistemology of science—the preeminent place of evidence rather than authority—that I hold up as the model for science instruction. It is my contention that particular ways of approaching science learning are more likely to be congruent with the needs the students our schools serve. That is, placing the authority to evaluate one’s own ideas and the ideas of others through evidence and consensus has the potential to dissolve or minimize barriers to student identification with science schooling by changing what it means to *do science* in school. Thus, by shifting the central practices away from a valuing of the recapitulation of the

endorsed narrative or canon of science knowledge to more closely resemble authentic practices of science, effective science curricula can be conceptualized as a meta-tool for engaging students in scientific inquiries, rather than a vehicle for imparting science “facts” to students. From this perspective, we may realize the opportunity to both engage students who have historically operated on the margins of science schooling and engage students of all backgrounds in more authentic scientific practices.

The resulting conceptual framework draws from three theoretical areas, critical theory, classical motivation theories, and sociocultural theories of learning and motivation. Critical theory provides the means to understand the enduring social and cultural dynamics that continue to keep various groups in the U.S. in the current, unacceptable system of relations. Further, a critical stance provides opportunities for the voices of marginalized populations to be heard and shared and for the power dynamics of the classroom to be analyzed. This awareness can lead to improved systems of relations and the creation of conditions in which the oppressed and the oppressor may act to free and empower themselves. I make the assumption that science schooling, which represents science as an authoritative body of knowledge is the oppressive factor that constrains access to scientific literacy and science futures for so many students. I do not go as far as to discuss the oppressive factors of the scientific enterprise, or entry into scientific practice as a profession. Though many sociocultural factors are at play, this is beyond the scope of the work presented here.

Classical theories of motivation provide a framework for understanding how particular classroom practices of evaluation and recognition function to encourage either productive orientations or failure-avoiding modes of engagement in the classroom. A sociocultural lens on motivation lends further insight to the classical theories by viewing the student, teacher, and setting as a dynamic context. This provides an analytical lens with which to examine the reflexive and interdependent processes of engaged participation in shared practices (or nonparticipation) and identity formation. Combined, these theoretical tools afford insight into existing and perpetuated inequities in schooling, classroom practices that function to either sort and marginalize students or provide a context for them to engage wholly and meaningfully in learning, and

inform hypotheses about how the learning environment may be reorganized to empower students through scientific induction.

Through this framework, this study seeks to address the following research questions:

- What practices are valued among students in a classroom modeled on scientific induction?
- How do students engage in scientific discourse and practices through the PET curriculum?
- In what ways do the structures and enacted practices of the PET curriculum encourage students from historically underperforming groups toward greater participation in classroom activities?
- In what ways do students' participation in scientific practices via PET and students' development of scientific identities mediate one another?

CHAPTER 3

THE PHYSICS AND EVERYDAY THINKING™ CURRICULUM

Physics and Everyday Thinking™ (or PET) is an NSF-funded, inquiry-based physics curriculum designed for undergraduate non-science majors (Goldberg, Robinson, & Otero, 2008). PET was designed as a semester-long course consisting of carefully sequenced sets of activities intended to help non-science majors and pre-service elementary teachers develop an understanding of physics through guided collaborative experimentation and questioning with extensive small-group and whole-class discussion. The curriculum follows a guided inquiry approach and focuses on the cross-cutting themes of interactions, energy, forces, fields, nature of science, models, and scientific explanations. By “guided inquiry” I mean that the curriculum is designed to engage students in engaging scientific questions, collect laboratory evidence to address these questions, and develop inferences that best explain the observed phenomena. The cross-cutting themes run through the curriculum and scaffolding support for the development of these cross-cutting concepts is provided throughout. The learning objectives address many of the benchmarks and standards for physical science found in the *National Science Education Standards* (1996), *AAAS Project 2061 Benchmarks of Scientific Literacy* (1993), and the *Next Generation Science Standards* (in Press).

The PET curriculum features two major course goals, a canonical physics content goal and a *Learning about Learning* goal. The purpose of the content goal is to help students develop a set of ideas that can explain a wide range of physical phenomena and that are typically included in introductory physics curricula. The purpose of the *Learning about Learning* goal is to help students become more aware of how their own ideas change, how knowledge is developed within a scientific community, and to better understand the relations between their own learning and how scientists learn and develop explanations about the natural world (nature of science).

The PET curriculum is divided into six chapters, shown in Table 3.1. Each of these chapters consists of a sequence of five to eight activities and associated homework assignments designed to address one or more of the

Table 3.1. The six PET chapters.

Chapter	Title
1	Interactions and Energy
2	Interactions and Forces
3	Interactions and Systems
4	Model of Magnetism
5	Electric Circuit Interactions
6	Light Interactions

benchmarks or standards. In most cases benchmarks or standards were broken down into a series of smaller objectives that are the focus of one or more individual activities. Each smaller objective builds on those preceding it toward the development of the broader benchmark idea that serves as the main objective of a sequence of activities. “Interactions” is a unifying theme throughout the curriculum, as can be seen in Table 3.1. Also, contrary to the traditional sequencing of topics in the physics canon, energy is addressed before forces. The decision to re-sequence the traditional canon reflects the research-based decision making that the development of this curriculum was informed by. This decision was based on two research findings: (1) PET developers found that energy appeared to be more aligned to students’ experience-based intuitions, and (2) these students were better able to develop understandings of forces and vectors after establishing a strong sense of energy and energy conservation.

In Chapter 1 students learn to describe interactions in terms of energy transfers and transformations, culminating in the development of the law of conservation of energy. Chapter 2 addresses students’ ideas about forces, and aims to develop an understanding of Newton’s second law. Students then use both energy and force approaches in Chapter 3 (focusing on magnetic, electrostatic, and gravitational interactions), and thereafter use either approach as appropriate throughout the remainder of the curriculum.

Each activity in PET consists of four activities or curricular structures: *Purpose*, *Initial Ideas*, *Collecting and Interpreting Evidence*, and *Summarizing Questions*. These structures were designed to help students engage in the scientific process by sharing their initial ideas and iteratively revising them in light of new evidence, collaborating with other students through experimentation and sense-making, and ultimately coming to consensus as a class on the central, evidence-based ideas that can explain phenomena.

Approximately 75% of the activities and homework assignments focus on helping students learn physics content. The remaining activities and assignments focus on *Learning about Learning*, where students are explicitly asked to reflect on their own learning, the learning of younger students, and the learning of scientists. These activities are embedded throughout the curriculum and in homework assignments and are important, not only because they help students investigate the nature of science and the nature of learning science, but also because they draw the teacher's attention to the design principles that guide the curriculum. The Learning about Learning activities follow the same structure as the content activities in which students state their initial ideas, collect and interpret evidence (often from videos of younger students learning similar content, readings from science education literature about students' prior knowledge, or readings from the history of science), and respond to and discuss summarizing questions. The Learning about Learning activities are hypothesized to supplement the physics content activities to help students develop a requisite level of scientific literacy. By *scientific literacy* I mean that the goal is for students to both understand the nature of scientific knowledge production and participate in scientific discourse and practices. Of course, the effectiveness of the Learning about Learning activities is dependent upon students experiencing the content focused activities in which students actually participate in scientific discourse and practices. As such, these two types of activities are interdependent in helping students develop a requisite level of scientific literacy.

The PET curriculum was designed and developed on the basis of design principles informed by research in both cognitive science and science education. These design principles are founded upon the idea that student learning is made possible by environments in which students articulate, defend, and modify their own ideas in order to actively construct conceptual understanding of the defined topic. The descriptions here are adapted from work describing and researching the PET curriculum (Goldberg, Otero, and Robinson, 2010; Otero and Gray, 2008). These design principles were developed from a framework of learning as conceptual change, and the language used through the following descriptions does contrast with the analytic framework of this study.

Design principle 1: Learning builds on prior knowledge

Research indicates that learners' prior knowledge plays a major role in how and what they learn (Bransford, Brown, & Cocking, 2003). Prior knowledge appears in social, emotional, linguistic, cognitive, and intuitive forms and comes from past experiences including those associated with formal education as well as everyday experiences. The literature on conceptual learning often focuses only on conceptual knowledge that is either incorrect or correct, but findings indicate that prior understanding can be useful or problematic for future learning (diSessa, 1988; Vosniadou, 2002; Hammer, Elby, Sherr, and Redish, 2004).

In the PET curriculum, each activity begins with a section called *Initial Ideas* in which students' prior knowledge about the central issue of the activity is explicitly elicited. Students record their own ideas about the topic first (for example, why a ball slows down and stops after being given an initial push), and then discuss their initial ideas in small groups. This is followed by carefully sequenced activities where students engage in *Collecting and Interpreting Evidence*, in which these ideas are further explored through experimentation. As might be expected, the evidence students collect supports some of their initial ideas and not others and frequently requires that students make modifications to their current ideas. Inferences about the phenomenon being explored are encouraged and guided by the *Summarizing Questions* section of each activity, in which students make claims on the basis of their evidence and support these claims in large class discussions.

Design principle 2. Learning is a complex process requiring scaffolding

Instructional approaches that leverage prior knowledge are often founded upon a view that learning is a process in which students iteratively modify their understanding. In this way students' experience-based ideas are reconciled with or merged into the particular language, symbols and concepts that are presented through formal schooling (Vygotsky, 1986). Instruction that helps students reconcile formal language and symbols to their experiences and to simultaneously generalize their experiences away from the concrete events to which they are tied helps students establish ideas that are meaningful to them

individually and also have broad explanatory power that may be relevant to a community (Brown & Spang, 2008). This process is complex and can be a lengthy, non-linear process. Thus progress toward some understanding can be facilitated by guidance and support (“scaffolding”) for students as they reconcile their current ideas in light of new evidence. As students move toward mastering a certain concept or skill, the degree of scaffolding can be gradually decreased.

The structure of the PET curriculum incorporates scaffolding supports for students’ progress and gradually decreases these supports for specific topics addressed within a sequence of activities as well as for themes addressed throughout a chapter, multiple chapters, or throughout the entire curriculum. Examples of themes addressed throughout the entire curriculum include the concept of evidence-based claims, explanations, models, and systems, interactions, and energy. In each case, significant guidance is provided initially, and then gradually removed as students gain experience working with these ideas.

Design principle 3. Learning is facilitated through interaction with tools

Learning within any scientific community depends to some degree on the use of tools such as specialized language and symbols, graphical representations, laboratory apparatus, and simulations that are necessary for communicating, supporting, and negotiating ideas (Vygotsky, 1986; Latour & Woolgar, 1986; Brown, Collins, Duguid, 1989). Science instruction in schools can also leverage such tools for communicating, supporting, and negotiating ideas as a means for developing new understanding. Although scientific inquiry within a classroom usually takes the form of an expedited, condensed, and guided version of real scientific inquiry, students can still learn how to utilize tools and practices of the discipline and explore how their learning is similar to that of scientists.

Throughout the PET curriculum, learning is facilitated through students’ interaction with tools such as computer simulations, laboratory apparatus, graphical representations and specialized representations such as energy diagrams and force diagrams. Students make connections between simulator-generated graphs and their own graphs generated using a motion detector. Specific questions help students make explicit connections between energy and force representations, thus calling students’

attention to the different ways that scientists represent the same thing. Specific questions also bring students' attention to other uses of tools, for example how scientists use evidence and how this is similar to how students use evidence in their own thinking and learning.

Design principle 4. Learning is facilitated through interactions with others

Learning within any discipline relies on negotiations and interactions among members of the disciplinary community (Latour, 1987, Vygotsky, 1986; Kelly, Crawford, & Green, 2001). In physics education, scholars have demonstrated that courses that allow students to interactively engage with one another show higher learning outcomes (Hake, 1998; Heller, Keith, and Anderson, 1992). Through engagement in collaboration and argumentation with one another, students articulate their ideas, defend their claims using evidence from their observations or explanations that have already been endorsed by the community, and modify their ideas in the light of evidence and arguments posited by their peers (Driver, Newton, & Osbourne, 2000; Van Zee & Minstrell, 1997; Cohen, 1994).

The PET curriculum is designed to be enacted as a collaborative enterprise. Students interact with one another both in small and large groups and throughout the learning process. In small groups students collect and interpret evidence and make model-based claims about phenomena they observe in their experiments. In large groups they present their evidence-based claims and engage in scientific argumentation about the validity of these claims. At the end of a whole class *Summarizing Discussion*, the class comes to consensus on a handful of big ideas that can be used to explain their observations of nature. At this point, the teacher hands out *Scientists' Ideas Sheets* that include these ideas along with the specialized language students are unlikely to come up with on their own. Implementers of PET report high success regarding students developing the appropriate ideas. This is likely due to the thorough research-based design and validation of this curriculum.

Design principle 5. Learning is facilitated through establishment of norms, practices, and expectations

Classroom norms and behavioral expectations and practices can greatly influence students' opportunities to learn in formal settings (Cobb & Yackel, 1996; Tuminaro & Redish, 2007, Gutierrez, Baquedano-Lopez, Alvarez, & Chiu, 1999). Teaching and learning science is much more than delivering and absorbing content, it also involves establishing a set of obligations and expectations within the classroom that are not only conducive to learning, but also are aligned with the obligations and expectations that define the disciplinary community (Gee, 1990; Airey & Linder, 2009; Jurow, Hall, & Ma, 2008; Sfard & Lavie, 2005). In order for students to become aware of her own initial ideas, they must feel that comfortable that this will not be a negative experience. In order to proceed to modifying and defending their ideas, they must feel comfortable both challenging others ideas and having their ideas challenged, and they must feel comfortable allowing shifting from viewing the teacher and textbook as the authority over what knowledge counts to one that takes nature and social consensus to be the authorities.

In the PET classroom community, students must take initiative in developing, testing, challenging, and modifying their ideas and those of their peers. There is no formal "textbook" used for the course, instead, students work through carefully sequenced and researched activities that guide them toward consensus on a handful of big ideas that can answer the key question of each activity and build up to the central scientific idea of each chapter (such as Newton's second law, Coulomb's law, or the domain model of magnetism). In addition, this curriculum explicitly helps students generate ideas about the nature of science, for example the role of models, explanations, and modification of ideas.

CHAPTER 4

METHODS

The purpose of this study was to understand how students experience the PET curriculum and to determine its potential effectiveness for expanding access to science for groups historically underrepresented in science. This study was conducted using qualitative methods in an attempt to understand the experiences of the people in this setting as well as develop explanations for their perceptions of the experience and an explanatory model for the mechanisms by which these outcomes were realized. The methods used draw from the ethnographic tradition and are consistent with LeCompte's (1999) characterization of ethnographic research.

One primary difference between *ethnography as science* and other social and behavioral science methods of investigation is that ethnography assumes that we must first discover *what* people actually do and the reasons they give for doing it before we can assign to their actions interpretations drawn from our own personal experience or from our professional or academic disciplines (LeCompte, 1999, p. 2)

This research relies on observing both the individual and communal actions of the subjects under study and their perceptions of the experience. Informed by a critical perspective, this approach values the perspective of the students under study who are largely from groups most often marginalized in science schooling, and considers their voices to be essential to understanding the nature of this curricular enactment. Interpretations of actions, then, must be consistent with the views of the actors. Likewise, analysis of and inferences drawn from the perceptions of the actors must be consistent with what we can glean from observing them in practice.

The execution of this study, particularly the analysis and conclusions, was consistent with what Maxwell (2005) calls an "interactive" model. Rather than a linear, uni-directional plan and progression, it was a reflexive process "in which any component of the design may need to be reconsidered or modified during the study in response to new developments or to changes in some other component (Maxwell, 2005, p. 2). Many iterations of viewing and analyzing video data, cross-referencing interview data with video data, and adjusting interpretations of interview data

based on video data were conducted in order to develop as accurate a characterization of this experience as possible.

Setting and Subjects

The setting for this study is a small, urban high school with a high proportion of students of low socioeconomic status from groups that are traditionally under-represented in STEM. Approximately 70% of students at this school are eligible for free or reduced lunch, and demographic data for the two sections are found in Table 4.1. A physics teacher at this school site has implemented the PET curriculum in her classes for two years. In the 2010-2011 school year, her second teaching with PET, I co-taught one of her four sections for the third trimester of the school year and spent a considerable amount of time co-teaching, observing, and collecting data in another. This allowed me to observe and collect data in her PET classes as a “fly on the wall” observer for some of her classes and to collect data and gain additional insights as the instructor in my own class as a participant observer.

Table 4.1. Demographic Data for PET Implementation Sample.

	<u>Section 1 (n=24)</u>	<u>Section 2 (n=25)</u>
Male	16 (67%)	12 (48%)
Female	8 (33%)	13 (52%)
African American	3 (13%)	---
Asian	1 (4%)	1 (4%)
Latino	10 (42%)	17 (68%)
Native American	1 (4%)	---
White	9 (38%)	7 (28%)

This small high school’s courses are structured such that every student will take physics during their 11th or 12th grade year. At this school, all students take the sole physics course, and the learning goals and means of meeting those goals prior to and during this study were the purview of the instructor alone. The students in this sample are representative of the general student population at this school in that all students are required to take physics, and there were no differences, such as ability grouping, considered in the scheduling of the four sections of the course offered.

It should also be noted that there are large numbers of English language learners and undocumented students at this school and these classes. In interviews of students, conversations with the teacher and other schools staff members, and in classroom conversations it became obvious that there were large numbers of students who were quite mobile, changing schools often and traveling to visit family in Mexico during the school year. Undocumented students also expressed frustration about their academic futures. They were quite aware that they or their parents would have to pay very high out of state tuition if they were to attend college. For those I spoke with, this would mean not going to college if another option did not make itself available.

The Teacher

At the time of this study, the teacher of the courses under study was in her third year of teaching and her second year teaching with PET. She has a bachelor's degree in biochemistry and a master's degree in urban education. She is a former Noyce Fellow and was selected as a Noyce Master Teaching Fellow in the Streamline to Mastery professional development program at the University of Colorado Boulder.

Data Sources

Data collected for this study include approximately 30 hours of video of classroom interactions, including both small group work and whole class discussions. The small group videos focus on a small sample of collaborative laboratory groups, and the whole class discussion videos were intended to capture as much of the activity of the whole class as was logistically feasible. I have also collected all of the chapter assessments, students' "lab notebooks," and administered the PET conceptual assessment (published with curriculum materials) at the end of the course. Finally, I conducted 13 individual interviews and two focus group interviews to gain insight into how students experienced the course.

From these data sources, a sample of videos from the various types of activities that make up the PET curriculum was selected, as shown in Table 4.2. The selections of video from within these parameters were further based on: the quality of video available (e.g., angle of the camera relative to the action of

interest, audio quality, etc.); the presence of students in the small group activities that were recorded who were also interviewed for this study; and the researcher's discretion that the selected videos were not unusual in any significant way (i.e., large numbers of students absent, activity designed to supplement the PET curriculum, etc.). Videos from each of three main types of activities in PET—Initial Ideas, Collecting and Interpreting Evidence, and Summarizing Discussion activities—were chosen. One full cycle of learning in Chapter 5, Electric Circuit Interactions is analyzed. Also analyzed were two other activities from two other units to demonstrate that the findings from the videos of Electric Circuit Interactions are not anomalous. The entire set of 13 individual and two focus group interviews was also transcribed and analyzed.

Table 4.2. Video Data Analyzed

<u>PET Activity</u>	<u>Unit</u>	<u>Date</u>	<u>Length</u>
Initial Ideas	2. Interactions and Forces	9-29-10	11:31
Initial Ideas	5. Electric Circuit Interactions	3-1-11	8:26
Collecting and Interpreting Evidence	5. Electric Circuit Interactions	3-2-11	13:54
Summarizing Discussion	5. Electric Circuit Interactions	3-2-11	16:00
Summarizing Discussion	6. Light Interactions	4-19-11	26:28

Units of Analysis

This study takes two different units of analysis as appropriate to address different research questions. To investigate the nature of students' experiences in this course, the unit of analysis is the student. Individual and focus group interviews were analyzed to determine how each student perceived the PET experience.

In the analysis of classroom video, this study takes a collective unit of analysis with regard to student activity. Specifically, when analyzing student engagement in the various activities of the PET curriculum, the four-person laboratory group was taken as the unit of analysis. The PET curriculum is structured such that laboratory groups are responsible for producing products to share with the class (initial ideas and answers to Summarizing Questions), thus the sense-making activity observed in the class was collective. Inferences made about students' developing ideas, as well as affective displays were analyzed at the group level. One exception to group level analysis was made when different levels of engagement

were observed within the group level. In the analysis of pedagogical moves that the teacher employed in classroom activities, the teacher was taken as the unit of analysis.

Analysis of Video Data

The video data were analyzed using an interpretive analysis approach (LeCompte, 1999). Each of the classroom videos was transcribed using Inqscribe™ transcription software. Five video segments were then selected for analysis from three of the five chapters of the PET curriculum, as shown in Table 4.2. Videos were selected from various chapters of the curriculum to provide the reader with a sense for the different subject matter that students experienced and to investigate whether or not there were differences in the ways that the students engaged with and the teacher enacted the curriculum. One full learning cycle from the Electric Circuit Interactions chapter was analyzed to provide the reader with insight into one entire learning cycle. Full analyses of all videos in the sample were conducted, but several analyses were presented in a condensed format for space considerations. The full analyses for the condensed versions are provided in appendices as indicated in the second results chapter.

The interpretive coding analysis involved reading through each transcript to investigate and determine the nature of the teacher's students' engagement with the prescribed activities of the course. Students' verbalizations were recorded along with prominent gestures and affective displays. The decision that one gesture or display was prominent, such as laughter, smiling, or "high-fiving" is a subjective one, and only obvious gestures and displays that required little inference were noted. When necessary, the video was watched repeatedly in an attempt to determine how the students engaged the PET activities, how the teacher facilitated student learning, and the evolution of students' ideas during these activities. Observations were made for each piece of transcript analyzed, and observations across activities were compiled and analyzed for observations that appeared across different activities and video samples. Observations that occurred across samples were taken as findings that applied to the entire sample.

Interview Data

Interview protocols were developed to investigate how students perceived the experience of the PET course. Individual interview questions were developed as a framework of items intended to elicit conversations about how they perceived the instructional experience, how this experience relates to the nature of scientific inquiry and knowledge, and how students see themselves in relation to future science-related endeavors.

The group protocol was developed to focus on the various curricular structures of PET and how these facilitated physics learning. For example, the Initial Ideas activities are atypical in that students are asked to present their ideas about a physical phenomenon before they have had any formal classroom experience about the phenomenon. Likewise, the Summarizing Discussions are atypical in that the students are expected to arrive at consensus on the scientific explanation that the class will accept. In the interviews, I investigated how the students perceive these non-traditional activities.

These protocols were developed as a very preliminary framework intended to be conversation starters rather than an exhaustive list of questions that needed to be addressed. My philosophy concerning interviews is that the productivity of an interview hinges largely on the extent to which the interviewer and participant(s) can engage in a conversation that follows the interviewee's emergent ideas. I believe that the more the participants can find themselves in natural conversation rather than answering a list of questions, the more productive the experience can be.

PET Individual Interview Protocol

General

1. What can you tell me about learning physics in Mrs. X's class this year?
2. How has this class been different from other science classes that you've taken?
3. What parts of the class do you think are most helpful to your learning?

How is that part helpful? Be specific.

4. What is your role in this course? How is it different from your expected role in other courses?
5. Is there anything else about this course that stands out for you?

Nature of Science

6. How is what you do in this class related to what working scientists do?
7. What does it mean to “know” something in science?
8. What makes science knowledge or knowing different from other types of knowledge, if anything?
9. Here is a claim (Insert something here that kids may be familiar with); do you believe it? Why or why not? What would it take to for you to be reasonably sure that this claim is factual?

Possible Futures

10. What are your plans after high school? Could you imagine yourself in a science or engineering career? Why or why not?

PET Focus Group Interview Protocol

1. Tell me about initial ideas. Do you feel that *Initial Ideas* is a valuable part of the class?
2. What if you’ve never thought about the phenomenon before (like what’s inside a magnet)? Is *Initial Ideas* still a valuable experience?
3. How does it make you feel to know that you may be wrong during *Initial Ideas*?
4. How do you feel when your initial ideas ARE right? Does that retract from the experience?
5. Do you think your background knowledge is a valuable thing? Why?
6. Are the laboratory activities valuable? Why or why not?
7. Are the summarizing discussions valuable? Why or why not?

Interview data were transcribed and coded using *open coding* methods (Strauss, 1987). The interview data were analyzed for emerging constructs and trends within and across individual students using NVivo™ analysis software. A initial coding scheme was developed based on intuitions about structures of the curriculum and associated interactions that could provide insight into students’ perceptions of the experience. From this analysis constructs emerged and trends were noted across interviews. The principal codes that emerged were related to classroom culture, the role and modification of ideas, valuing the tools and practices of science, students’ perceived roles, and classroom power structure. The initial coding scheme is shown below.

Initial Codes:

- Talk
- Power
- Nature of Science
- Identity
- Ideas
- General Perceptions

After some iterations of coding small subset of the interviews, the coding scheme was expanded to elaborate some of the categories, as shown below.

Refined Codes:

- Talk
 - Summarizing Discussions
 - Community
- Power
 - Sanctioning Knowledge
 - Roles
- Nature of Science
 - Evidence
 - Consensus
- Identity
 - Talk
- Ideas
 - Valuing
 - Modifying
- General Perceptions

Further iterations of coding and analysis resulted in a narrowing and reorganization of the coding scheme.

The final coding scheme is shown below, along with descriptions of the codes.

1. **Comfort**: Students statements indicate that they were comfortable expressing their physics ideas publicly in class.
2. **Ideas**: Students expressed an awareness of the role that their own ideas play in the learning process (Metacognition).
3. **Scientific Practices**: Students statements indicate that they value engaging in scientific practices such as supporting claims with evidence, requiring evidence for others' claims, and constructing explanations through consensus.
4. **Roles**: The nature of teacher facilitation and student participation in this course is different from previous courses the students have experienced.
 - a. Students statements indicate that they perceived the teacher's role and/or power structure in this course to be different than in traditional classes.
 - b. Students statements indicate that they perceived the nature of their own participation in this course to be different from their participation in previous science courses.

Once the principal constructs became apparent, they were investigated across all students' interview responses to compile the proportion of students that "endorsed" a particular view. For example, 11 of 14 students interviewed made statements indicating that they became comfortable sharing their ideas publicly in class.

Interview Coding Reliability

In order to assess the reliability with which the emerging construct codes were applied, another researcher coded one focus group and two individual interviews (20% of the interview data set). This researcher is a science education doctoral student who is familiar with the project, and has had formal courses and experience conducting in qualitative research. We performed an initial one-hour session in which he learned about the codes and practiced applying them to a small sample of data. The other researcher then independently coded the three interviews. A simple joint agreement was applied to the three independently coded interviews and resulted in an inter rater reliability of 84%.

Developing an Explanatory Model

Once interview data were analyzed, it became clear that these students perceived the PET experience to be overwhelmingly positive and one that contrasted markedly with their past experiences. Thus, it became one goal of this research to develop an explanatory model for the positive student perceptions of this experience.

Thus, a systemic approach to determining what essential factors made such an experience possible was employed. A consideration of the nature of student engagement in the context of the principal

curricular structures and dominant practices of the classroom, particularly the teacher's practices and means of facilitating student sense making, were considered in light of the findings from the interview data to extract the essential factors that resulted in a dramatic departure from traditional science experiences.

This process resulted in the development of an explanatory model for the PET experience, as shown in Figure 4.1. Of course, the full explanatory model will be presented in the final chapter of this thesis.

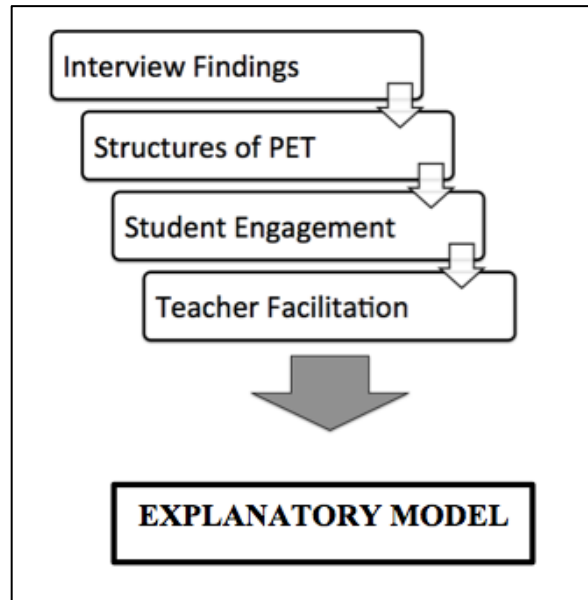


Figure 4.1. Development of the Explanatory Model

CHAPTER 5

RESULTS I: INTERVIEWS

In this section, I describe the students' experiences in the course. These experiences are characterized from statements made by students in individual and focus group interviews. I present evidence that students perceived this experience to be markedly different from their past science experiences as well as experiences in other subjects. I further show that one result of this novel form of experience was students indicating that they had developed positive relationships with both physics and scientific practices in general, such as evidence-based reasoning and skepticism. We found that the students in this course:

- (1) became comfortable expressing their physics ideas and came to value having their ideas challenged and challenging the ideas of others;
- (2) expressed an awareness of the role that their own ideas play in the learning process;
- (3) came to value engaging in scientific practices such as supporting claims with evidence, requiring evidence for others' claims, and constructing explanations through consensus;
- (4) perceived the teacher's role and power structure in this course to be different than in traditional classes and that this aspect had impacted the nature of their participation.

Table 5.1 below shows a summary of evidence supporting the above findings. This table shows all students interviewed and the type(s) of interview each student participated in. Checked boxes indicate that evidence supporting each of the four findings listed above was found in each respective students' interview statements. Ten of the fifteen students participated in both individual and focus group interviews, three participated in individual interviews only, and two only participated in focus group interviews. A clear majority of students made statements that led to each of the four findings.

Table 5.1. Interview evidence supporting findings.

Student _n	S ₁	S ₂	S ₃	S ₅	S ₆	S ₇	S ₉	S ₁₀	S ₁₁	S ₁₂	S ₄	S ₈	S ₁₅	S ₁₃	S ₁₄
Data	I, F	I, F	I, F	I, F	I, F	I, F	I, F	I, F	I, F	I, F	I	I	I	F	F
Finding															
1	√	√	√	√	√	√	√	√	√	√			√	√	
2	√	√	√	√	√	√		√		√	√			√	
3	√	√	√	√		√	√	√		√	√	√	√		√
4		√	√	√	√		√		√		√	√	√		

*Data type: I = Individual Interview; F = Focus Group Interview

Comfort Expressing Initial Ideas

By the end of the course, students overwhelmingly agreed that they came to feel free to express their ideas in the PET classroom. It is clear, however, that they were initially uncomfortable sharing their ideas publicly. When asked to retrospectively reflect upon how they had felt about having to voice their ideas at the beginning of the course, they responded:

David: *Because at the very beginning it was like “How are we supposed to answer this? We don't know.”*

Laura: *I myself was like “Why?” Like I was just not used to the whole structure.*

Chris: *I was a little skeptical.*

Sonia: *Yeah, we were just kind of like, “Uh...”*

Chris: *It sounded pretty bad.*

Laura: *I was thinking, “I want to switch classes.”*

Sonia: I noticed that in the first summarizing discussion, I saw other people were scared to share out. Because we didn't know each other, we were afraid of how we were going to be judged or get looked down on.

These statements show that students remembered being apprehensive about publicly sharing their ideas. David recalls feeling exasperated and not having any idea how the students “are supposed to answer this.” Chris expressed that he was “skeptical” and that what they were asked to do sounded “pretty bad.” One student, Laura, even stated that she considered changing her schedule to avoid the PET class. Sonia states

that she observed others were “scared” to share their ideas, and that they were “afraid” of being both “judged” and “looked down on.”

In spite of their initial reservations, students grew to meet these expectations for public sharing and consistently spoke positively about the sharing of initial ideas. When asked what they thought of Initial Ideas near the end of the course, students shared the statements below:

Chris: *I think Initial Ideas are good because it gives—we get to see all the ideas that come to the table.*

Tina: *I think they are [good] just because everyone has their own ideas.*

David: *Even if you hadn’t thought about it before, it gets you to do that and start thinking about it and get interested.*

Laura: *Because we all have like different background knowledge that are applicable that adds to our initial ideas.*

José: *And then like the reason I like the Initial Ideas is because you could put pretty much whatever answer you want. It doesn’t have to be right. And then you pretty much go back and talk about what you think and why you think that. And then like you’d hear somebody else’s thoughts and then like you could build up on this.*

Lily: *Well, coming in with like an idea of what we are going to be learning, and then just coming out with like a broader, deeper thinking.*

Above, Chris states that the Initial Ideas activities are “good,” and Tina agrees. José expresses that the initial ideas don’t “have to be right.” These responses illustrate that students’ valued expressing their ideas in a context in which being correct was initially not expected or required. These students also appear to value a context in which they could see the diversity of ideas on the topic. Chris expresses that Initial Ideas are “good” because they “get to see all the ideas that come to the table.” Likewise, Laura expresses that they “all have different background knowledge,” and Tina thinks Initial Ideas activities are good because “everyone has their own ideas.” These responses suggest that students’ comfort with expressing their ideas

may have arisen, at least in part, from seeing the diversity of ideas other students expressed and thus growing more comfortable with their own naïve and developing ideas.

Metacognitive Awareness of the Role of Ideas in Learning

When asked if Initial Ideas is a valuable part of the class, students expressed sophisticated views of the role their initial and developing ideas play in the learning process. They seemed to understand that the purpose of eliciting their initial ideas was so that they could modify their thinking toward more scientifically accurate ideas, as illustrated below.

David: *Yeah, I think so because you may say that background knowledge it kind of helps other students like get a –if they don't have an idea of like initial idea of what's going on in there and actually background knowledge will kind of help them create a starting point into the lab.*

Maria: *It's just like the building blocks. It's like starting with at least something. I mean starting with nothing is really hard to build up an idea. But if you have at least a minimal building block and somebody, even if it's not correct, it helps to build your idea.*

Lily: *Science or physics is just different. Like you have your own thought and we always have to twitch our own thoughts, and it's different from any other class. Like history, you know what you are going to be learning about. Physics is you think of something and you have to twitch it.*

Researcher: *Do you mean “tweak it” or “refine it?”*

Lily: *Yeah.*

These statements suggest that these students came to value their own prior knowledge as an entry into or a starting point in the learning process. David states that “background knowledge will help them create a starting point,” and Maria adds that “starting with at least something” can help “build your idea.” These statements indicate that these students feel that a productive learning process may start with what one

thinks initially. Lily expresses an awareness of how her own ideas and the ideas of her classmates were modified in this context. Further, she attributes this phenomenon, that of making an initial idea explicit and then refining it, to the broader constructs of science and physics. She contrasts this with the rest of schooling, stating that “it’s different from any other class” and giving an example and contrasting it with physics: “Like history, you know what you are going to be learning about. Physics is you think of something and you have to twitch it.” She describes learning in physics as starting with one’s own ideas, whereas she appears to perceive learning in other subjects to be very different.

Comfort Expressing and Challenging Ideas

The statements from students above expressing their initial anxiety over public sharing of ideas suggest that activities like the Initial Ideas operate in direct contrast to the general expectations of schooling. These expectations, as described in the theoretical framework, encourage students to “do school” or to seek correct and often superficial answers to rote questions or tasks rather than seek understanding (Jimenez-Aleixandre, et al., 2000; Pope, 2002). However, given appropriate structure and expectations (the nature of such teacher facilitation is discussed more in Chapter X), students articulated that they could express their ideas and conclusions freely as well as challenge the assertions of others without fear of being made to feel anxious or negative about themselves. When asked how they came to feel comfortable expressing themselves in the PET class students responded:

David: *Well, it’s just like we are in this environment that you know we may be wrong but it’s like nobody is going to tear you apart because of it. You know it’s not like “Oh you’re wrong. You are stupid. Go do something else,” you know.*

Lily: *Because we got comfortable eventually, and Ms. Belleau makes us comfortable with each other. Like she doesn’t – like if we are wrong or something she doesn’t like criticize us. We share with the group. She doesn’t tell us, “Oh this is wrong, or this is right. We share ideas with each other and that’s when we like, come to consensus. You know, this is right or this is wrong. I think we’ve just become comfortable with it.*

Maria: *So I think I've become more confident in my answers. It's because before I was just like "I don't know if this is right and if I am not right, I don't want to be told I am wrong, so I am not going to say anything." But now, if I am wrong it's not – like Lily said it's not "You are wrong" it's "Well, let's build up your ideas and see how that goes."*

Moises: *The big thing is you work with more people, so you are expected to share things and your ideas, so you expect to be wrong sometimes...Well, it just depends on the thing really. Like now that we are getting into the hard physics, I am usually wrong most of the time in the beginning, but after I know how it works, I get it.*

Laura: *I mean it doesn't matter if it's wrong.*

Researcher: *Why not?*

Laura: *Because, Initial Ideas it's better if you're wrong. Because if you're right from the beginning it's boring. You don't argue. You don't have a discussion.*

The excerpts above suggest that students were comfortable sharing naïve ideas, expected themselves and others to be initially scientifically inaccurate, and came to value refining of their ideas and consensus building in the PET class. Their statements also appear to index another world—one that contrasts sharply with the PET class. In their attempts to describe the PET experience, many students illustrated what they thought PET was *not*. According to David, the PET class isn't a place where someone will "tear you apart" or tell you "You are stupid" and "Go do something else" for being "wrong." Likewise, Lily shares that the teacher didn't "criticize us" for being "wrong." Maria describes her own thoughts before experiencing the PET class: "I don't know if this is right and if I am not right, I don't want to be told I am wrong, so I am not going to say anything." David, Lily, and Maria describe the PET class by contrasting it to their prior schooling experiences, which they convey as being marked by a reluctance to participate over fears of the consequences of being "wrong."

In contrast, all of the students above indicated that being "wrong" is acceptable in this environment. Lily uses the word "comfortable" three times to describe herself and others in this setting and is supported by Maria in her view that they will not be judged by the teacher about how correct their ideas

are. Maria also expresses that she has become more “confident” in her answers, though she was previously reluctant to speak out if she wasn’t sure she was “right.” Likewise, Moises expresses that that being “wrong” is “not necessarily a bad thing” in this physics class.

Valuing Scientific Practices (Evidence-based arguing and challenging)

Along with growing to feel comfortable expressing themselves, it became clear that many students came to value and enjoy critiques. By stating that being right in the beginning is “boring”, Laura shows how much she values argumentation and discussion. Though it is not evident in the data that *all* students value this sort of critical engagement, her statement reveals that she did (more data supporting students’ affinity for critique will be presented in classroom dialogue in Chapter X), and statements below suggest that a supportive environment that encouraged risk-taking developed. The statements below indicate that a culture of critical inquiry, the seeking of greater understanding through challenging one another’s claims, was established among these students.

José: *Like in the beginning maybe we were—maybe we were afraid that they’d judge us in what we thought. But we grew more and more each trimester to where we got comfortable around each other and just whatever you think that we know it’s OK to think wrong, you know.*

Chris: *Yeah, I definitely agree because I didn’t know my class and obviously if you don’t know something you are not going to like to share your ideas and share how you thought something worked.*

Maria: *Because we help each other. Like we come in with like with our initial idea. And even if it’s wrong we like we, I don’t know. Like people – other people give us confidence like “Oh no, this is what’s wrong about it” or “I think this.”*

David: *There has never been an instance where it’s just been you know us by ourselves. It’s never been one person, it’s part of a whole group. That’s what I was going to add to hers is that we have groups instead of just us.*

Laura: *And you wouldn't like to like argue with them because you would think they would take it wrong. So we just grew with each other and realized it was right to argue with each other because we were all doing it to help each other, not just to make you look bad in the circle and stuff.*

The conversation above illustrates how students initially feared being wrong, were afraid of being judged, and initially didn't feel comfortable sharing an answer if they didn't "know something." José expressed that the students had been "afraid they'd judge us in what we thought." Chris states that you are not "going to share your ideas" if you don't "know something," and Laura expressed her concern that others would take critique the wrong way.

In spite of the reservations and fears that these students brought with them into the PET classroom, they "grew" more "comfortable" with, as José says, "whatever you think." He echoes Lily's statement from above that the students grew comfortable with each other and with the notion that it's OK, even productive, to be "wrong." Maria shares that they disagreed with and critiqued one another in order to "help each other." Laura states that the students "realized that it was right to argue" because they were doing it to "help each other" rather than to make each other "look bad." Likewise, Maria states that disagreement and critique actually leads her to greater "confidence."

These students' affinity for critiques developed concurrently with, and was perhaps contingent upon, their coming to value evidence as a basis for supporting claims. Evidence, rather than the teacher or textbook, became the authority. As students stated above, they were able to overcome being afraid of being judged or made to feel stupid because they were "wrong." It is plausible, that by replacing "authority" with evidence, students were able to allay their fears of being judged and develop a more accurate understanding of what scientific argumentation is. When asked how disagreements over explanations are settled in the class, students offered these statements:

Laura: *Like, what's your evidence? Your evidence then, like, "Well, I saw this"...like just telling them straight up, "Prove it. Prove that you know."... I was like "Oh, how so?" you know like I just kept asking questions. Like we asked how – I know all of you guys like from the discussion*

circles and we are not gullible like we are not just going to believe something, because we want that evidence.

Moises: *Not if they don't have any evidence because then you don't know if they are lying...It depends on how they use their evidence.*

...

Researcher: *OK. And is that something particular to this class or do you think that's something that's part of Physics or science?*

Moises: *I think it's really a part of physics. I have been wrong a lot in this class, and it's not necessarily a bad thing because you learn from your mistakes.*

David: *Yeah, you can't just say like, for instance, "Oh when I threw water in the air, it just stayed in the air." You got to have evidence it stayed there. It's like it wouldn't work obviously because it's, you know, common knowledge, but I'm just saying as, you know, an example, you have to have evidence to prove that that actually did happen. That it would be true you know, I guess that's also a personal view, but I just you know you have to have evidence to back it up.*

Sonia: *Like it's exactly like court. You would play, like waste all your time trying to figure out the evidence, trying to put your things together and try to win your case, and then you go to the court and that's what I think like it comes down to and you are going to get an answer there. So you are going to get – you got to be prepared.*

In the excerpts above, students are quite clear that the standard for making a convincing claim is the support of evidence. Each of the five students quoted here refers directly to the need to present evidence to support a claim. Laura states that they are “not gullible” and that they need evidence to believe something. Moises demonstrates that he is skeptical of the claims of others, and that those making claims must use evidence in particular ways to be convincing. Sonia describes the process of argumentation and consensus building using an analogy of a court of law. Rather than receiving information from the teacher, she describes a context in which she and her classmates prepare for discussions and then “try to win your case.”

Flattened Power Structure/Different Teacher's Role

By design, this curriculum displaces the typical location of authority with teacher and text to evidence and consensus. Of course, such a change in classroom power structure may be afforded by curriculum design but is ultimately contingent upon the actual enactment of the curriculum. Factors such as fidelity of implementation and instructor epistemology will impact the nature of the classroom power dynamics. In this case, analysis of the interview data revealed that some students appeared to be both aware of and articulate about the non-traditional role of the teacher as well as the reorganization of the traditional power structure of the classroom. For example:

Laura: *Because we just came to like concluding that that's what sounded right, and then Ms. Belleau was like I think you guys figure that out yourselves. Like, she doesn't really talk, she just asks questions.*

Chris: *She like guides us in there. If we get off topic then she'll like asks a question that will cause us all to like get back on track. Like she doesn't tell us where to go. She like gives us the option to go that same direction.*

These students expressed that they perceived the teacher's role to be that of a guide in the learning process rather than a giver of information and a decider of what is right or wrong. These statements show that students perceived the power (and responsibility) to find answers had become theirs. Laura remarked that the teacher told them to "figure that out yourselves" and that the teacher "doesn't talk (lecture), she just asks questions." Likewise, Chris expressed that the teacher "doesn't tell us where to go" and that she "guides us" and "asks questions."

Another student, Phoebe, also recognized the different structure of the PET class and was particularly articulate about what was different.

Phoebe: *I feel like when classes like that, I feel like we're on like on equal ground. Like us and the teacher too. Like we know that she knows it more but she wants us to like be on her level if that's what she thinks. Come on, I know you know, you just need to put it into words and just like explain it right. But I'd like in that class I didn't feel like it was like she was like this is the answer because*

I said so. It was like we were talking about this is the answer because we saw it and we know you know. So we're just trying telling you. Like, I feel like that's how it was.

Researcher: *So you think – you really think then that you're – or do you really think then that you relate, your sort of relationship to the teacher is different?*

Phoebe: *Yeah. It made me feel a lot more comfortable in that class. Like I felt a lot more comfortable asking questions like I didn't feel like she was going to be like "Oh, you're wrong."*

Researcher: *Uh huh.*

Phoebe: *I feel like that's why a lot of people don't ask questions because they don't want the teacher to be like "Oh, no that's not the right answer" like...*

Researcher: *Yeah. Or why would you think that?*

Phoebe: *Yeah. Yeah. Like it was never like that. And like at first I never really ask questions in discussions like I was like I don't want to ask questions, I don't want to be wrong and I don't want to be heard to be like you're wrong and nobody take that off your grade or something like...*

Researcher: *Or just feeling dumb.*

Phoebe: *Yeah. Like specially in front of like your classmates because like I think a lot of times people were confused and then, like one person will ask a question, people would be like "Oh, yeah, I didn't know that either." Why like...*

Researcher: *It's almost always somebody else has that question.*

Phoebe: *Yeah, for sure. Especially since we like also have the same thing because not everybody is like on the same page and we all know what's going on. But it was really nice. Yeah.*

Researcher: *Okay. So it made you feel comfortable. It made you feel less pressure from the teacher right?*

Phoebe: *Yeah. Yeah.*

Researcher: *Then you said it sort of brings her to your level, right?*

Phoebe: *Yeah.*

Researcher: *What do you mean by that?*

Phoebe: *Like, I don't know. When you're in the class sometimes, it just feels like the teacher is always like great and everybody else is like smarter than you and they have all the answers and like I think...*

Researcher: *Yeah. Keep talking. I'm going to check this (the camera).*

Phoebe: *...when she did that like it felt like we have the answers also, we just needed to discover them. Like it wasn't like you don't have the answers and I do. It's like we all have the answers.*

Researcher: *How so? How do you have the answers? You're just the students can you?*

Phoebe: *Because we saw it. We saw it. Like I think we just like all know that we just need somebody to be like there is the answer.*

Phoebe's remarks offer remarkable insight into the PET learning environment. She states that she feels that the teacher is "on her level" and on "equal ground" and contrasts this feeling with a class where "it just feels like the teacher is always like great and everybody else is like smarter than you and they have all the answers" and that the teacher tells you the answer is the answer because "I said so." These remarks reference a very typical classroom power relationship in which the teacher and text are the sole source of sanctioning knowledge. Thus, students must look to an authority figure or text to determine what counts as knowledge and what does not. Clearly, Phoebe felt that the PET classroom setting, and the roles within it, were very different, and that they, the students, "have all the answers." That is, the students have both the means and the power to arrive at their own conclusions. When I asked how the students can have all the answers, Phoebe replied "Because we saw it." This idea, that they *know* because they *experienced* it, was common among the students.

David: *Because if you know, if you saw it like with your own eyes, and you tested it then you know for sure that's what's going to happen.*

Laura: *We need to see the process of what scientists have to go through to figure out like our answer. So it's like life experience and then only...it's so much better to actually see it, than to just hear it.*

Lily: *And then he brought one in the circle and we did the experiment in front of everybody, and then you know it helped us. We were like “oh”.*

Sonia: *We had our own ideas and then we actually tested it out and the observations like how to understand that, “Oh we were correct.” And here is stronger evidence... Because you have to have an explanation, you have to have an experience. Yeah, I think like that’s what labs have to put in, like you experience the actual model. You experience the unit, not just hear about it.*

These statements reveal that students related to the experience of gathering and making sense of evidence in very significant ways. Laura and Sonia both express that to understand one needs to experience the phenomenon, rather than “just hear about it.” For them, experiencing the physics with their own bodies and minds is a significantly different way of seeking knowledge than being told what it is that they should know.

Overall, the students perceived this experience to be markedly different from past experiences in school and in their other science classes. When asked to compare this experience to others they have had in school, students responded:

David: *Well, it’s just like we are in this environment that you know we may be wrong but it’s like nobody is going to tear you apart because of it. You know it’s not like “Oh you’re wrong you are stupid. Go do something else” you know. It’s...*

Researcher: *Do you feel that way in some of your other classes besides Ms. Belleau’s?*

David: *Well, not really.*

Maria: *She is like our first real science teacher that is like legit.*

David feels that this is an environment in where “nobody is going to tear you apart” for being “wrong,” and states that this is the only class in which he experiences this. Maria feels that this is her first “real science teacher” and that this teacher is “legit” (*legit*, slang for legitimate, is used frequently by students to refer to something highly favored, authentic, and part of their world).

José: *Because we did it and we know it works.*

Researcher: *M-hmm...and when you say “it works,” like the whole...*

José: *Like the whole process and how any goes from like initial ideas, to your little individual groups, and then group discussion and then summarizing questions.*

Researcher: *OK, so you feel like the whole thing you got is effective?*

José: *I think if we got like summarizing discussions like in most of our classes that we'd be doing a lot better than just listening to the teacher talk, you know.*

Researcher: *Why?*

José: *Because when we just sit there and listen to the teacher talk, like most of the things she is saying that we are not going to get, you know. So I think if we all come together and like prepare one question and talk about that question and like provide our evidence, I think we'd all build up each other in whatever subject we fit.*

Sonia: *I think in math especially because I think us students are in math class, I think we are really struggling in our class because it's just like she is [inaudible] talk, talk, talk, talk you are just like you kind of like...*

José states of the entire experience and its structural components that “we did it and we know it works” and expresses a desire to have some of the structure of the PET class—the summarizing discussion—in his other courses, because he finds them so useful. Sonia agrees with José that all their other teachers do is “talk, talk, talk, talk,” and that this is an ineffective strategy for learning, especially when compared to discussing evidence and coming to consensus.

It was not uncommon for students to state that they had previously not liked science or thought that they were not cut out for science and that this experience had changed how they view themselves with respect to science.

Chris: *But now, this year, science is my favorite subject.*

Lily: *It's been like very interesting. I have learned so much than I have ever learned in any science class. And science class is one of my weaker subjects in school, so I think like how Ms. Belleau teaches is very helpful.*

Researcher: *OK. So Sonia, what can you tell me about Ms. Belleau's physics class?*

Sonia: *It's fun and it teaches me a lot, like the first time I have ever liked a science class.*

Researcher: *You never liked science class before?*

Sonia: *No. I was horrible at science.*

Researcher: *What do you mean?*

Sonia: *I didn't understand the concepts, like the terminology and the vocabulary and just why things happened. I didn't really quite understand, and when I didn't understand, I kind of gave up.*

...

Sonia: *Because you have to have an explanation, you have to have an experience. Yeah I think like that's what labs have to put in, like you experience the actual model. You experience the unit, not just hear about it.*

...

Sonia: *She actually like makes us get our hands dirty and investigate why this is it.*

...

Sonia: *Because they would just kind of tell us, "OK, you are going to do this and this." But then when they expect you [inaudible]. So we were just kind of on our own like trying to get there, and most of the time we didn't get there because we had other people that didn't understand and we just kind of moved off. And in Ms. Belleau's class you have like step by step. And it instead of just being step by step and then a question, its steps, why do you think this, you have to have your hypothesis, so it's kind of like all built in together.*

Researcher: *Oh, I see you wanted it but you [Inaudible].*

Sonia: *Yeah I wanted it, I needed it and then most of the time I didn't get it, so that's what kind of caused me to not really like science.*

Researcher: *Yeah for sure. Well, I'll tell you that sitting in a chair and having someone tell you something is not science.*

Sonia: *It's boring.*

Researcher: *All right, great. Is there anything else you want to tell us about physics or anything like that?*

Sonia: *I never thought I would like it but it's become my favorite class.*

Dion: *[looks at the camera] Ms. Belleau, you changed our thinking.*

Lily's and Sonia's stories are particularly interesting they never liked or felt successful in science but came to feel success in this course. Sonia is aware that she never got what she really needed, hands-on experience and scaffolded instruction, to understand the science. She even knows now that the lack of quality instruction is what "caused me to really not like science." Likewise, Lily states that science is one of her "weaker subjects in school" and shares that she has learned more in PET than she has "ever learned in any science class." Finally, Dion is aware that his thinking has changed. In retrospect, I regret not following this thread further, but it is safe to say that his statement that the teacher "changed our thinking" is quite significant. One plausible inference from this statement is that Dion is aware that the way that he processes external information has changed as a result of this experience and perhaps the way he interacts with the world has changed too.

It is clear that these students felt that this experience was markedly different from their other science education experiences. In their statements, the students appear to be indexing two contrasting worlds. The first is a world in which they are bound by anxieties over needing to be "right," they are anxious that they will look "stupid" in front of others, and they are both "gullible" and "afraid" to challenge the assertions of others. The second is an experience in which they are relatively free of fears of being "wrong," have come to know that it "is right to argue" because they do it "to help each other," and one in which they have both the tools and means to understand the world and challenge the assertions of others. Words and statements made by students that index these contrasting worlds are presented here in Figure 5.1.

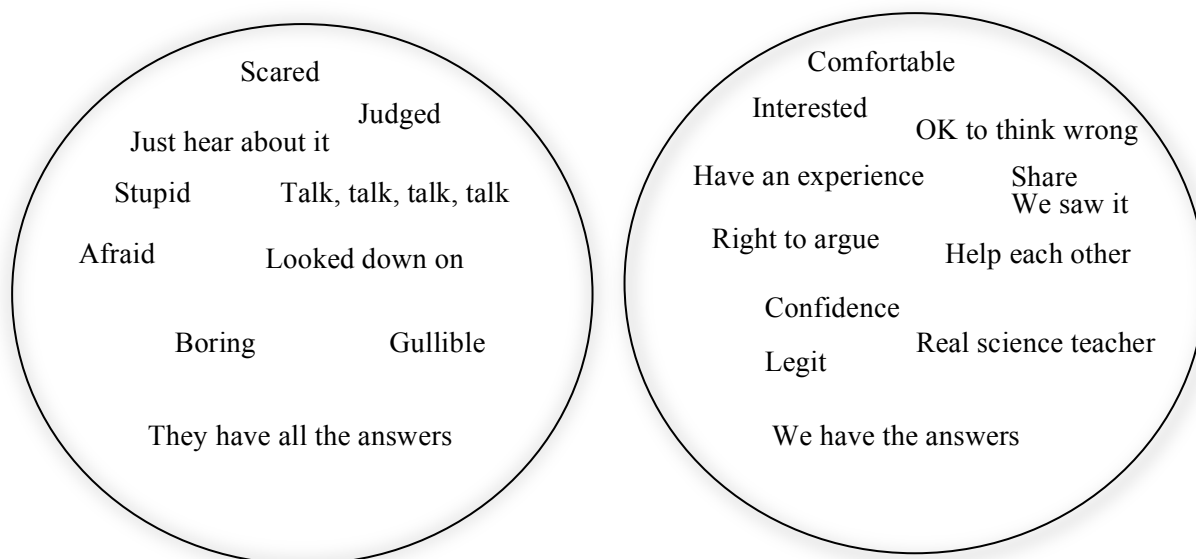


Figure 5.1. Students’ statements indexing contrasting worlds.

We see through the students’ perspective that the PET classroom is a place where they feel “comfortable” expressing their ideas, initial and developing. Where it is “OK to think wrong,” and “sharing” and challenging ideas is a means to “help each other” and become more “confident” in what they know. It is also a place where they may attempt understand the physical world via “experience”, rather than “just hear about it” and one in which they have the power to seek and arrive at answers under the guidance of a “real” and “legit” science teacher. This world appears to contrasts starkly with the bulk of their other schooling experiences, which make them feel “judged,” “afraid” to challenge others, or “stupid” if they do not know the answer that the teacher wants them to regurgitate. They feel that most of school is boring and that they are expected to be “gullible” and listen to teachers, those that “have all the answers,” “talk, talk, talk, talk” so that they can “just hear about” the science, rather than *experience* it.

The sum of these experiences appears to have had a transformative effect on these students. Stating their initial ideas, collecting evidence, making meaning from that evidence, and seeking consensus among themselves appears to have instilled in these students a sense that they are now different in some significant way. In their words:

Sonia: *We used to be gullible before this class. We just took the information from the teacher and we were like, “OK, you’re right, I guess.”*

***Laura:** Because there won't always be a person holding your hand telling you this is right. And Ms. Belleau pretty much does a great job of telling us you know you got to figure it out yourself. You got to stand on your own two feet and figure it out for yourself because you are not always going to have that person that's going to tell you "yes, you are correct" or "no, you are not."*

***Maria:** So, like I think we've become, because we are expected to have evidence, I think we've become more of like in control of our education and like the choices we make so we kind of – and the information we are taking in and I think we've become more I guess open to the idea that we are in charge. So if we, you know, we need the information, we are going to ask for it. We are not going to sit around anymore and just have an OK explanation. We're not going to settle anymore, I guess.*

Sonia actually articulates that she used to be gullible. She had previously accepted what the teacher told her without even knowing that she could, and should, understand it and question it. I infer from this that she realized that she previously felt disempowered and came to reject the notion of accepting someone else's truth with no means for understanding it and no power to dispute it. Likewise, Laura came to realize that she could and had become empowered to seek answers on her own. I further infer that she came to understand that the artificial way that much of traditional schooling encourages students to seek approval for answers, rather than developing within students critical thinking and the sense of agency it entails, will not prepare her for life beyond school. Maria also recognizes her own transformation and that of her fellow students. She actually attributes her sense of greater control to her experiences collecting and prioritizing evidence as a means to sanction knowledge. It is clear from her statements that she feels a sense of agency and a sense of empowerment over her own education that she has not felt before.

In summary, students in this class began the course feeling anxious about sharing their ideas publicly. However, they grew to value giving voice to their own ideas, as well as the ideas of others, and developed an awareness of the role of their initial and developing ideas in the learning process. These students also came to value supporting claims with evidence as well as challenging the assertions of others. They perceived this experience to be markedly different than their past science education experiences in

that the role of the teacher was more of a guide to help them find answers, rather than a dispenser of information. Finally, a small number of these students even expressed a greater sense of control and agency in their own learning. These students were aware that they had previously been uncritical consumers of authoritative knowledge and had come to see that they could, and should, be skeptics, demand evidence for assertions, and take more control over their own learning.

CHAPTER 6

RESULTS II: CLASSROOM VIDEO

This second chapter of findings is derived from analysis of classroom video. A sample of videos from the various types of activities that make up the PET curriculum was selected for analysis to determine (1) how students engage in the PET activities and (2) how the teacher facilitates these activities. Videos from each of three main types of activities in PET—Initial Ideas, Collecting and Interpreting Evidence, and Summarizing Discussion activities—were chosen. One full cycle of learning in Chapter 5, Electric Circuit Interactions is analyzed. Also analyzed were two other activities from other units to demonstrate that the findings from the videos of Electric Circuit Interactions are not anomalous. As stated in the Methods chapter, selections of video from within these parameters were further based on: the quality of video available (e.g., angle of the camera relative to the action of interest, audio quality, etc.); the presence of students in the small group activities that were recorded who were also interviewed for this study; and the researcher’s discretion that the selected videos were not unusual in any significant way (i.e., large numbers of students absent, activity designed to supplement the PET curriculum, etc.). The details of the selected videos are shown in Table 6.1.

Table 6.1. Video Sample

<u>PET Activity</u>	<u>Unit</u>	<u>Date</u>	<u>Length</u>
1. Initial Ideas	Interactions and Forces	9-29-10	11:31
2. Initial Ideas	Electric Circuit Interactions	3-1-11	8:26
3. Collecting and Interpreting Evidence	Electric Circuit Interactions	3-2-11	13:54
4. Summarizing Discussion	Electric Circuit Interactions	3-2-11	16:00
5. Summarizing Discussion	Light Interactions	4-19-11	26:28

The three principle activities in the PET curriculum are, in order as they occur, Initial Ideas, Collecting and Interpreting Evidence, and Summarizing Discussions, as shown in Figure 6.1. The Initial Ideas activities are relatively short events in which students are presented with questions about physical phenomena and asked to state their best answer before having any formal experience in this course related

to the topic. Each student first answers the Initial Ideas questions individually, each lab group (usually made up of four students) then comes to consensus through discussion, and finally the group presents their answer to the class. In the Collecting and Interpreting Evidence activities, students address questions posed in the Initial Ideas activities by collecting and making sense of laboratory or computer-based simulator evidence. The Summarizing Discussions are

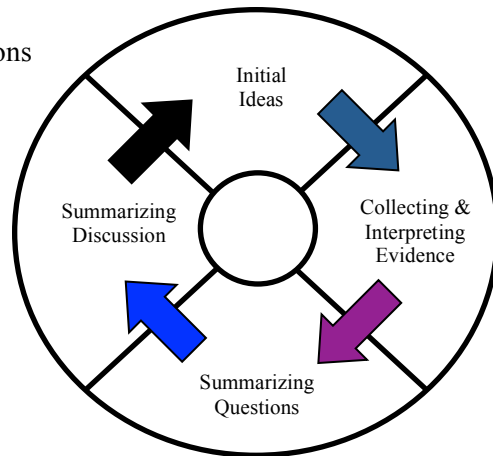


Figure 6.1. PET Learning Cycle

teacher-led, whole class discussions in which the class attempts to come to consensus on the central questions of the given activity. The summarizing questions are designed to support students in making sense of data, constructing models, and developing general principles supported by data. Much like the Initial Ideas activities, each student answers the questions individually and then each lab group is expected to come to consensus and present their conclusions to the class. However, expectations for Summarizing Discussions are unlike the Initial Ideas activities in that the class is expected to come to consensus on the answers that best explain the laboratory observations they have made during the most recent Collecting and Interpreting Evidence activity.

The findings of the previous chapter strongly suggest that the students' experiences in this course was markedly different from their past school science experiences, and in this chapter I examine:

(1) exactly what the students are doing in this context in order to gain further insight into why they valued this experience so highly; and (2) what the teacher does to facilitate student activity that makes such an experience possible. Each video was analyzed to answer two central questions:

- *How do students engage the assigned tasks in this learning environment?*
- *How does the teacher facilitate learning in this context?*

Key findings from these analyses are:

1. **These students were guided by the curriculum and the teacher through the process of *scientific induction*.** This evidence-based, inductive reasoning entailed making many specific, concrete observations of physical phenomena and then moving inferentially to the development of a general, abstract scientific principle. These students' participation in the inductive process is marked by persistence, emotional expressions of frustration and enjoyment, and what appears to be a commitment to understanding the phenomenon they are tasked with investigating.
2. **These students appear to enjoy engaging in scientific induction.** This enjoyment is evidenced by smiles, gestures of accomplishment and congratulations, and compliments for one another about completing the task.
3. **The teacher employed three pedagogical strategies to facilitate students' scientific induction:** (1) deferring to laboratory evidence to sanction students' ideas and explanations by avoiding the traditional school practice of evaluating students' ideas and encouraging students to test them for themselves; (2) affirming student effort and sense-making with both benign comments, such as "interesting" and compliments that appeared to value students' efforts, as opposed to openly valuing students' correct ideas; and (3) employing "on the fly" pedagogical strategies and tools, such as drawing student's attention to differences between the different possible configurations of the lab apparatus and the associated concrete observations they were making.
4. **The students took ownership of the process of Summarizing Discussions.** They led the Summarizing Discussions and dictated the course of the activity by deviating from the standard script of the activity to redo the light experiment.
5. **Student engagement in these tasks is marked by unequal participation.** Within the lab group analyzed in this chapter, two of the four students handle the lab equipment exclusively and interact with each other and the teacher much more than the other two students.

Initial Ideas

Analysis of Video 1 – How do students engage the Force Interactions Initial Ideas task? How does the teacher facilitate this task?

The Initial Ideas activities occur at the beginning of each topic and were designed to elicit students' prior understanding about the physical phenomena they are about to investigate. This task is designed to make students' ideas explicit so that students become aware of their own initial ideas and the ideas of their peers. This process is analogous to positing a hypothesis as an initial step in a scientific inquiry, and in PET the Initial Ideas activities serve as an entry into the process of guided classroom scientific inquiry. Once students' ideas are made explicit to themselves and others in the classroom, they can become aware of the iterative modification of their own ideas through reconciliation with laboratory evidence and social consensus building.

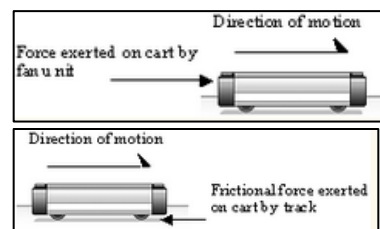
Background

A video of an Initial Ideas activity is analyzed here to determine how students engage this task. In the previous chapter, students investigated contact interactions through a framework of *energy transfers*. It is so common for students to conflate the concepts of *energy* and *force* (Clement, 1983; McKloskey, 1983), that the authors of PET chose to explicitly address this by engaging students in the investigation of contact interactions through the *energy* framework in Chapter 1 and then through a *force* framework in Chapter 2. This video is from the first activity of Chapter 2, Interactions and Force, which begins with students investigating the central question: *When does a force stop pushing on an object?* According to the PET Teachers Guide, the intent of the first part of Chapter 2 is for students to confront the common alternative conception that *motion implies force*. Research into common student conceptions has revealed that students often use an alternative conception in which they state that a force continues to act upon an object after the contact (e.g., the contact of a soccer player's foot with a ball) has ended (Clement, 1983; McKloskey, 1983). The target ideas, taken directly from the PET Teachers guide, addressed in the first part of Chapter 2 are shown below in Figure 6.2. It is important to note that the target ideas are never shared with the students. They are expected to arrive at these target ideas through scientific induction.

Target Ideas:

- The interaction between two objects may be described in terms of the force (a push or pull) that one object exerts on the other. To describe a force fully we need to know its strength **and** its direction. The strength of a force is measured in units of newtons (N).
- Forces act between objects only while they interact, and are **not** transferred from one object to another. (However, if one object is in motion while a force acts on it, then energy is transferred to, or from, the object.)
- A **force diagram** uses arrows to represent the forces acting on an object at a **particular moment**. The length of the arrow represents the relative strengths of the forces. When an object is in motion, its force diagram should also include a speed arrow to show in which direction it is moving. Two examples are shown below:

1. Force diagram for a cart moving to the right and being pushed in the direction of motion by a fan unit.
2. Force diagram for a cart moving to the right but being pushed to the left by a frictional force that opposes its motion



- If a single force acts on an object at rest, the object will begin to move in the direction of the force.
- If a single force acts on an object in the same direction as its motion the objects speed will increase. (When the speed of an object changes scientists say it is **accelerating**.)

Figure 6.2. Target ideas from Chapter 2.

In this Initial Ideas activity, students have responded to the prompts in Figure 6.3 individually.

Initial Ideas Prompts:

Think about a soccer player kicking a stationary ball. As he interacts with it, by kicking it, the ball starts to move. After the kick, the ball rolls across the grass and gradually comes to a halt.

- Sketch a speed-time graph for the motion of the ball. Be sure to include both the motion of the ball while the player's foot is touching it, and its motion after the foot has lost contact with it.
- Using a different colored pencil, indicate the period on the graph during which you think there was a force pushing the ball forward. Again, explain your reasoning.



Figure 6.3 Initial Ideas prompts.

Note that the reading of the questions by students in the transcript that follows may vary slightly from the text from the curriculum provided above, because the teacher has modified some of the wording to make the text more accessible to her students.

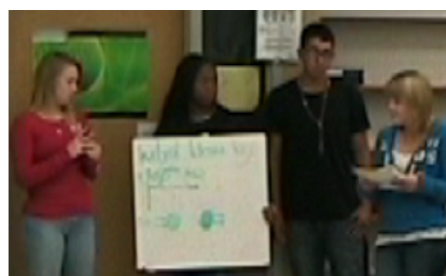


Figure 6.4. Initial Ideas presentation.

After responding to these prompts individually, students attempted to come to consensus within their lab groups and write their responses on a whiteboard in preparation for the sharing of these answers with the entire class. Presentation is shown in Figure 6.4. This video begins with the teacher telling the students which questions they will answer in this activity. The questions the teacher refers to in the transcript below as #3 and #5 correspond to the two questions provided above in Figure 6.3. The following analysis provides excerpts of the transcript intermixed with analysis of the transcript.

- 1 **Teacher:** So, today we're gonna talk about questions three and five. Question three actually relates to question one, so can somebody...can I have one person volunteer to read the little scenario that we're talking about before the questions?
- 2 **Denise:** Wait, on this page [points to sheet]?
- 3 **Teacher:** This one [points to question]. [Denise raises her hand] Alright, you guys quiet down while Denise reads it.
- 4 **Denise:** [Reading from her paper] Think about a soccer player and a stationary ball. As he interacts with it by kicking it, the ball starts to move. After the kicked ball rolls across the grass it gradually comes to a halt.
- 5 **Teacher:** So, a soccer player is kicking a stationary ball. What does stationary mean?
- 6 **Many students:** Not moving.
- 7 **Teacher :** OK, so there's a soccer ball. The soccer player comes up and kicks that ball that's not moving, causing it to roll along the grass and slowly come to a stop [The teacher physically acts out kicking a ball]. Alright, so in question one, you drew a graph. For question three, you showed where...I'm sorry, you showed where the forces were acting on the ball. And then question five—will somebody read question five?
- 8 **Doug:** [Reading from his paper] Now draw two pictures of the ball and each of them show the forces [inaudible].

- 9 **Teacher:** So, we have some pictures of the soccer ball and we use arrows to show the forces that are interacting on the ball. So, um, starting with group six, will you guys stand up and share your question...reading question five? [One lab group stands to present]
- 10 **Denise:** For question three it says [reading from her paper] 'Using a different colored pen, label (on the velocity-time graph) where forces are acting on the ball to push the ball forward. Explain your reasoning.'
- 11 **Denise:** Well, we didn't have different colored pencils, so what we did was underneath it [inaudible] we drew a line going up...or increasing because when the forces were acting on the ball the ball had forces that moved, so it was increasing instead of decreasing.
- 12 **Teacher:** So, is that the whole time that you see that there's force on the ball?
- 13 **Denise:** Um...
- 14 **Teacher:** Will you just use your finger to show me where you think there's force on the ball on the graph? [Denise points to leading edge of the curve and traces a line ascending to the top of the curve (Shown in red in Figure 6.5)].
- 15 **Denise:** OK. For five, draw two pictures of the ball to show what forces are acting on the ball. OK. Well, when the person is kicking it, the ball is receiving the force, so the force is going towards the ball. But after the guy is done kicking it, the force leaves the ball. So, that's why the arrows are coming out.
- 16 **Teacher:** Thank you. Thank you very much, group number six. May I see that whiteboard? Wonderful. Thank you. Alright, group number five. [Group five gets up] So, group five had some incredible discussion, and I didn't catch all of it, but will you guys be sure to share some of the discussion that you had, or the debate as you called it for question three.

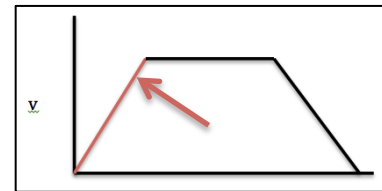


Figure 6.5. Reproduction of students' whiteboard

The teacher begins the segment above by making sure the students understand both the logistics (line 1) and the meaning (lines 5 and 7) of the task at hand. Denise then gives her lab group's first answer in line 10, suggesting that the group thinks that the ball speeds up under the application of force by the soccer player's foot.

“...we drew a line going up...or increasing because when the forces were acting on the ball the ball had forces that moved, so it was increasing instead of decreasing.” (line 10)

Although the group's answer to the first question suggests that they think the ball is only being acted upon by the force of the kick when it is speeding up (horizontally), it is unclear what is meant by “the ball had forces that moved.” The teacher asks for clarification of the group's graph in lines 11 and 13, asking the students to point to “where you think there's force on the ball in the graph.” Denise then gives the group's response to the second question in line 14.

“Well, when the person is kicking it, the ball is receiving the force, so the force is going towards the ball. But after the guy is done kicking it, the force leaves the ball. So, that's why the arrows are coming out.” (line 14)

The statement, “when the person is kicking it, the ball is receiving the force”, suggests that these students think that the force is only acting on the ball when the foot is in contact with it. However, this statement also indicates that these students may think that a force is something that is transferred from one object to another. It is also unclear whether or not the statement “...the force leaves the ball” suggests a *motion implies force* conception by indicating that the students' think the ball will slow as the “force leaves the ball.” Alternatively, Denise could have intended “the force leaves the ball” to mean that the force is no longer being applied to the ball.

In line 15 above, the teacher thanks the group and compliments them with “wonderful.” The next lab group takes the floor, and the discussion continues.

17 **Teacher:** Alright, go ahead.

18 **Aron:** Alright, I thought that, uh, this is their drawing [points to graph on whiteboard]. I thought that, uh, there would be no force after the dude kicks it, because there's a

difference between force and energy, so the force applies the energy, and then just gives it the energy, and it slows down. It loses the energy. And they [inaudible].

19 **José:** We were thinking that the whole time the ball moves, it's the force moving the ball, so that the whole time it's moving like the force made it move. So that's how it stops because the force on the ball stops. So, we were debating if it's gravity is what is friction is what makes it slow down. So we were debating if gravity and friction is a force as well.

20 **Teacher:** Sorry, will you say that one more time?

21 **José:** We were having a debate whether friction or gravity was a force as well.

22 **Teacher:** That's a good question, and we will investigate throughout this chapter. Are gravity and force—I'm sorry—are gravity and friction forces? Good question. You guys really fleshed out a lot of ideas. Like you brought energy into it. You really thoroughly talked about that question number three. I'm very impressed. Will you share your question number five?

In line 18, Aron begins by giving the group's first answer and immediately reveals that the group has not reached consensus. He points to the drawing on the whiteboard and says "this is *their* drawing," making it clear that the drawing on the whiteboard represents his other group members' ideas and not his. He then goes on to explain that the force of the kick only acts on the ball when the foot is in contact with the ball.

"I thought that, uh, there would be no force after the dude kicks it, because there's a difference between force and energy, so the force applies the energy, and then just gives it the energy, and it slows down. It loses the energy." (line 18)

In his answer above, Aron changes the conceptual framework from *force* to *energy* by stating that, "there's a difference between force and energy, so the force applies the energy," and asserts that the ball "slows down. It loses the energy." Aron has changed the rules of the conversation from the new framework, *force*, to the more familiar framework from Chapter 1, *energy*. He explains that he thinks that the force is the mechanism for the transfer of energy, and that as the ball slows down it loses energy.

In the next line, José gives an alternative to Aron's answer with the common alternative conception that motion implies force, further suggesting that the group had not actually come to consensus before taking the floor.

“We were thinking that the whole time the ball moves it's the force moving the ball, so that the whole time it's moving, like the force made it move. So, that's how it stops because the force on the ball stops.”

José states that if the ball is moving, then a force is moving it. This contrasts with Aron's explanation that the “force applies the energy,” suggesting that José thinks that force decreases as the ball slows, and that the ball stops when the force stops. Then in line 21, José shares that his group was debating another point and wondering if there was another “push” that was slowing the ball down. The teacher does not weigh in or otherwise resolve the debate, assures the students that they will investigate that question later, and compliments the students' efforts.

The presentation continues.

23 **Erin:** Well, I think there's a [inaudible] was a force, so I didn't really know.

24 **Doug:** We didn't know if there's a second, um, push.

25 **Teacher:** So you—sorry, I want to make sure I hear all the rest of Erin's thoughts, but really fast, you weren't sure if there was a second push.

26 **Doug:** Yeah, we know there's a push going to the ball with the, I guess, kicking it, but we weren't sure if there was like after if there was still a force after the kick.

27 **Teacher:** OK. Very interesting. Erin, did you get to say everything you wanted?

28 **Erin:** Yeah.

29 **Teacher:** Yeah? OK. Very nice. Thank you very much group number five. Group number four. [Group four gets up]

Though a critical part of Erin's statement is inaudible, Doug's next statements in lines 24 and 26 suggest that he and Erin are not sure if there is a second push after the initial kick. The teacher responds “very interesting” in line 27 and “very nice” and “thank you” in line 29. Also of note in this Initial Ideas

activity, though the word “push” was used here twice by Doug in lines 24 and 26, and the colloquial term “dude” was used by Aron in line 18, the teacher did not correct these students with more formal language or otherwise discourage them from using everyday language.

The next group takes the floor.

- 30 **Rodolfo:** For question three, we said that there was a force acting on the ball until like [inaudible] kicks it. We said that right here where he kicks it that's where the force stops. We said like, there has to be another force acting on it that makes it slow down...like friction or gravity or other force that slows it down and stops it. [inaudible sentence]. Right here we showed that [inaudible] a force [inaudible]. The kick adds a force to it (A in Figure 6.6) and right here (B in Figure 6.6) there's a force that makes it slow down.

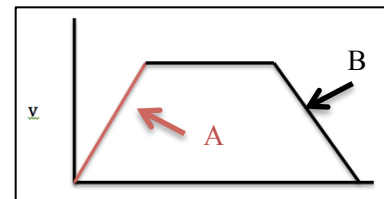


Figure 6.6. Reproduction of students' whiteboard

- 31 **Teacher:** Awesome. Very nice. Thank you so much for sharing.

Above, Rodolfo answers for his group, stating that there is only a force acting on the ball from the kick when it is actually being kicked. He further states that “there has to be another force acting on [the ball] that makes it slow down.” The teacher does not evaluate the accuracy of the group’s answers and responds “awesome,” “very nice,” and thanks the group. The activity continues with three more groups presenting their ideas, but is truncated here because redundancy is apparent. The remainder of the transcript is provided in Appendix A.

Analysis of this video segment reveals that the students in this video state their answers, try to support them with logical reasoning, and do not always come to consensus in the absence of laboratory evidence. The students’ answers presented here ranged from common alternative conceptions to ambiguous blends of accurate and inaccurate statements to statements that were scientifically accurate. These ideas are summarized in Table 6.2.

Table 6.2. Students' initial ideas for C2A1

Student	Statement	Inferred Student's Idea
Denise	"Well, when the person is kicking it, the ball is receiving the force, so the force is going towards the ball. But after the guy is done kicking it, the force leaves the ball."	Probably <i>motion implies force</i> , but unclear. (Inaccurate)
Aron	"I thought that, uh, there would be no force after the dude kicks it, because there's a difference between force and energy, so the force applies the energy, and then just gives it the energy, and it slows down. It loses the energy."	Force during contact. Energy associated with motion. (Accurate)
José	"We were thinking that the whole time the ball moves it's the force moving the ball so that the whole time it's moving like the force made it move so that's how it stops because the force on the ball stops."	<i>Motion implies force</i> . (Inaccurate)
Erin & Doug	"Yeah, we know there's a push going to the ball with the, I guess, kicking it, but we weren't sure if there was like after if there was still a force after the kick."	Force during contact, but unclear whether or not a force is "transferred" to the ball. Aware that there may be another force to slow the ball. (Ambiguous)
Rodolfo	"We said that right here where he kicks it that's where the force stops. We said like, there has to be another force acting on it that makes it slow down...like friction or gravity or other force that slows it down and stops it."	Force during contact. Aware that another force must slow the ball. (Accurate)

In spite of the range of accuracy of the answers, the teacher offered nearly identical responses to each, complimenting the groups' efforts and thanking them for sharing. Thus, we find that in this Initial Ideas activity, the teacher refrains from making any evaluative statements about students' ideas. Further, when students used everyday language when expressing their ideas, such as "dude" and "push" (rather than force), the teacher made no attempt to correct them, require more formal language, or otherwise discourage them from using informal language in their answers.

Observation: *In this Initial Ideas activity, the students share a range of ideas of varying degrees of scientific accuracy. Though most students use formal language, such as "force," some use informal language when sharing their ideas.*

Observation: *In this Initial Ideas activity, the teacher refrains from making any evaluative statements about students' ideas, including allowing everyday language to operate in the classroom.*

Analysis of Video 2 – How do students engage the Electrical Circuit Interactions Initial Ideas task?

How does the teacher facilitate this task?

In this section, another episode of Initial Ideas is analyzed to investigate commonalities across the Initial Ideas activities in different chapters of the curriculum. This begins the first of three analyses in the Electrical Circuits chapter, showing a complete learning cycle.

Background

In this activity, students make predictions about whether or not each of the six arrangements of a light bulb, a battery, and a wire, shown in Figure 6.8, will light the bulb. This activity is the students' first introduction to circuits in this curriculum, and begins to address two of the target ideas of this chapter, shown in Figure 6.7.

Target Ideas:

- An electric circuit interaction occurs when a source of electrical energy is connected in a closed path of conductors to an energy receiver. If the path is opened, or a non-conductor (insulator) is placed in the direct path, then the electric circuit interaction will cease occurring.
- Each device in an electric circuit is two-ended; and each end must be directly connected in the circuit. (If only one end of a device is connected in the circuit, then the device or the circuit will not work.)

Figure 6.7. Target Ideas Chapter 5.

These configurations are developed from research on common student ideas about circuits (Goldberg, Otero, & Robinson, 2010). One example of a common alternative conception is the idea that only the tip

(bottom) of a bulb must be connected directly to the energy source to function. Another example is the idea that something flows out of the positive and negative ends of a battery and collides in the bulb to produce light, referred to in the literature as the “clashing currents” model (Goldberg, Otero, & Robinson, 2010). Configuration #5 in Figure 6.8 is designed to address the “clashing currents” conceptual model.

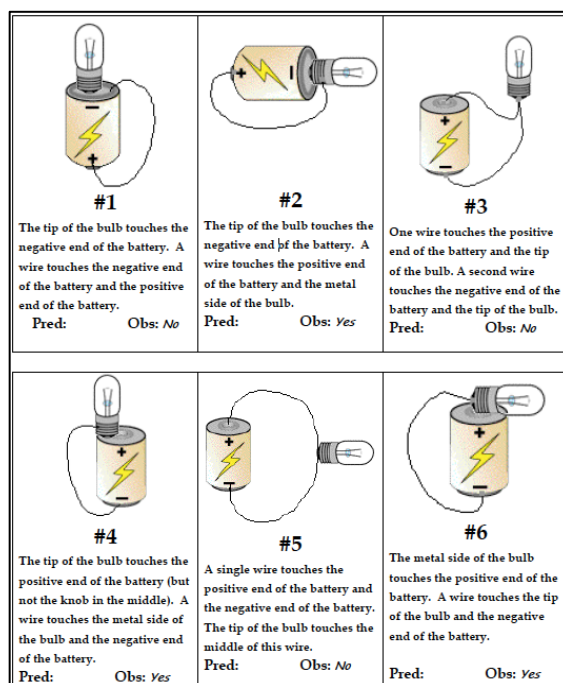


Figure 6.8. C5A1 Initial Ideas

After making these predictions in the Initial Ideas activity, students manipulate the apparatus shown in Figure 6.9 to answer the following questions:

Guiding Questions:

- Which part or parts of the battery need to be part of the connections?
- Which part or parts of the bulb must be touched to make the bulb light?
- How do the two ends of the battery need to be connected to the two sides of the bulb?

Figure 6.9. Guiding questions Chapter 5.

After experimenting with and answering questions about each of the configurations in Figure 5, students are to conclude that the bulb must make contact with the positive and negative ends of the battery (either directly or through a wire), and that the bulb must be touched on the side by one pole of the battery and on the bottom by the other pole, as shown in Figure 6.10. This allows electricity to flow in one direction, thus causing

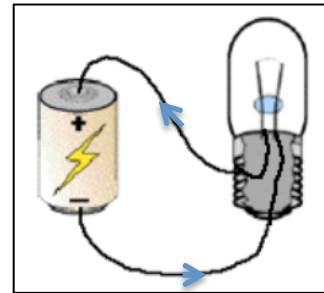


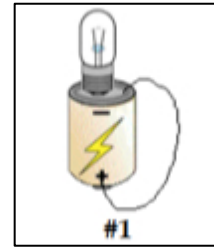
Figure 6.10. Connecting a light bulb

the tungsten filament to illuminate due to the high resistance of this material. The video selected for analysis here was taken at the start of Chapter 5, Electric Circuit Interactions, and the handout for the activity can be found in Appendix B.

The students have made predictions, both individually then in their lab groups, as to whether or not the configurations in Figure 6.8 will light the bulb. They have not yet manipulated any lab equipment or otherwise investigated the phenomenon of interest. The teacher begins the Initial Ideas activity by telling the students that this episode of sharing their initial ideas will be different from what they are used to. Because of time constraints, the teacher chose to shorten this activity by abbreviating the sharing of explanations for the students' predictions.

- 1 **Teacher:** Alright, so here's how we're gonna do this. Um, I want us to have time to test (the experiment) today, so we're only gonna share our initial ideas...briefly, OK. It's not gonna be like the normal stand up and explain everything. Here's how we're gonna do this. I am going to find up here which arrangement we're talking about, and I'm going to point to your group and I'm gonna go: group 1, group 2, group 3, group 4, group 5, group 6.

And you're just gonna say yes or no as a group. And then I'll call on two people to explain their thoughts. Cool? Alright so...arrangement number one has a battery, a light bulb, a wire, going to the ends of this battery (points to configuration 1 from Figure 6.8, shown at right). I wanna hear what we think. This group.



2 **Craig:** Um we said 'no' because...

3 **Teacher:** Don't explain yet. [Craig slams hand on table in disapproval] I know. I'll call you in a minute. OK, so, no. [Teacher points to next group]

4 **Group 2:** No.

5 **Group 3:** No.

6 **Group 4:** No

7 **Craig:** OK, moving on. Number 2.

8 **Teacher:** Uh, ssshhh (to Craig).

9 **Group 5:** No.

10 **Group 6:** No.

11 **Teacher:** Interesting. OK, Craig, explain why.

12 **Craig:** Um. Well, because the negative is the ground, which has to touch the side of the bulb, which is the ground. And the positive has to come to the bottom of the light bulb to light—to, uh, transfer the electricity.

13 **Teacher:** Oh, interesting. So, you're talking about the parts of a light bulb. [Craig nods.] Interesting. OK, thank you for sharing. I need one other person to share. Yeah, Sonia.

14 **Sonia:** Because um, we need the positive and the negative um charge to make something work. So, if you want to make the light bulb light you would have to make it touch the wire because that's where the negative and positive come together.

- 15 **Teacher:** Interesting. Thank you so much for sharing. Anyone else want to add anything?
 Alright, lets move on to number two. Number two. It looks kind of similar. What's the
 difference, though?

In the segment above, all groups respond ‘no’ when asked whether configuration 1 will light the bulb. In line 11, the teacher responds, “interesting,” to their predictions. Craig offers an explanation for his prediction in line 12. His use of terminology not yet introduced in the course (i.e., “ground”) suggests that he may have prior experience with circuits. He explains that the negative must touch the side of the bulb and the positive must touch the bottom, or tip. The teacher remarks, “interesting,” to his explanation, states that he talked specifically about the parts of the bulb, and thanks him for sharing. Sonia offers an explanation as well in line 14, suggesting the “clashing currents” model referred to earlier. The teacher remarks, “interesting” to her explanation too, and thanks her for sharing.

The teacher moves on to configuration number two, asking, in line 15 below, what the difference is between configurations one and two.

- 15 **Teacher:** Interesting. Thank you so much for sharing. Anyone else want to add anything?
 Alright, lets move on to number two. Number two. It looks kind of similar. What's the
 difference, though?

- 16 **Dion:** it's touching the side.

- 17 **Teacher:** Lisa did you have something else to add? OK. Alright.
 Same thing. We're just gonna go around the groups with yes's and
 no's. Group one.

- 18 **Group 1:** No.

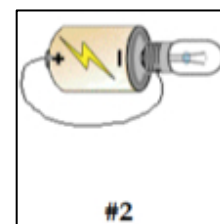
- 19 **Teacher:** Group one says 'no.' Group two.

- 20 **Group 2:** No.

- 21 **Teacher:** Group 3.

- 22 **Group 3:** Yes.

- 23 **Teacher:** Group 4.



- 24 **Group 4:** Yes.
- 25 **Teacher:** Ooh. Group 5.
- 26 **Group 5:** yes.
- 27 **Teacher:** Group 6.
- 28 **Group 6:** Yes. Oooh. [Many outbursts, hoots, cross the room hi-fives]
- 29 **Teacher:** Ah, no. We're very split. OK, someone from this table. [Lots of talking, laughing] Remember...let's be in a place--we can have fun, but let's make sure we're listening to everyone. Um, will someone from this table explain why you think. [Malcom explains but cannot heard because of others talking] I'm so sorry, there are people who aren't listening. You guys as people share their ration...Craig we'll have more opportunity to talk about it further in a second, but right now let's listen to Malcom. Go ahead, Malcom.
- 30 **Malcom:** The bulb is touching the negative part of the battery, and the wire is going from the positive part of the um, metal part of uh [inaudible].
- 31 **Teacher:** Thank you for sharing. Someone from the 'no' group. Tell me why.
- 32 **Sonia:** Because um...the wire has to touch the negative part.
- 33 **Teacher:** 'Cause the wire has to touch what?
- 34 **Sonia:** Um, the negative side of the battery.
- 35 **Teacher:** Oh, interesting. Oh, you're saying because the wire is not touching the battery.
- 36 **Sonia:** It doesn't make the circuit work.
- 37 **Teacher:** Thank you very much. Same thing for arrangement number three. Let's go. Group number one. [Several students talk at once] That's an interesting question. So, let's hold on to those questions and go on to number three. That way we have time to test it. Group number one.

For configuration two, there is disagreement between groups, and this brings some excitement to the room, as show in lines 29 and 30, marked by increased talking and laughing. Malcom offers an explanation in

line 30, though the audio prevents drawing clear conclusions about his group's idea. The teacher thanks him for sharing. Sonia offers an explanation as well, stating that it will not light the bulb because the wire is not touching the negative pole of the battery. The teacher responds, "interesting" and thanks her.

Below the groups give their predictions for configuration number three.

32 **Group 1:** No.

33 **Teacher:** Group number 2.

34 **Group 2:** Yes.

35 **Teacher:** Group number 3.

36 **Group 3:** Yes.

37 **Ray:** What number are we on?

38 **Teacher:** We're on this one.

39 **Ray:** I said yes.

40 **Teacher:** Group number four.

41 **Group 4:** Yes.

42 **Teacher:** Group number 5.

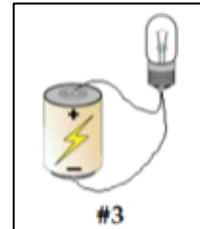
43 **Group 5:** Yes.

44 **Teacher:** Group number 6.

45 **Group 6:** Yes.

46 **Teacher:** Interesting. So...[lots of chatter] Hey you guys, let's re-norm this real fast. When we're sharing our initial ideas, we might have some...we might have some questions that we come up. We might um be curious about what somebody else said or revise our thinking. Let's—I love it. Definitely keep doing that, but let's be sure we're also listening to other people. Alright, so we kind of had a mixture here as well. From someone who said 'no,' will you explain why? Craig, go ahead.

47 **Craig:** Because the bulb's not grounded, and it has to make a complete...because they're both hooked up to the one spot, and it has to be--well I think--it has to be grounded by the



side of the bulb and the hot wire goes into the bottom of the bulb. But if they're both touching in one spot it can short out the circuit.

48 **Teacher:** Interesting. So, you're saying that because they're touching in one spot, it won't light up. [Craig shakes his head]. Thank you for sharing. From someone who said 'yes.' Um, maybe someone from that back table. James, John, Emilio. What were your thoughts?

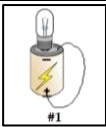
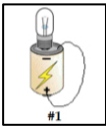
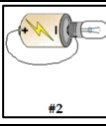
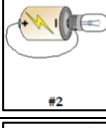
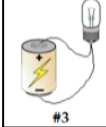
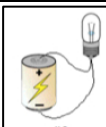
49 **John:** We said because the wires were connected to the bulb [inaudible].

50 **Teacher:** So, because the wire's connected to the bulb. OK. Thank you guys for sharing. Let's go on to number four. Um, group number one, what do you think?

Again, the groups share their answers. There are a lot of side conversations, so the teacher reminds the students of the norms for class discussions in line 46. Craig offers an explanation in line 47, stating that the bulb will not light because the wires are connected to the bulb in the same place. The teacher remarks, “interesting,” and restates Craig’s answer. John also gives his explanation in line 49, stating that the bulb will light because the “wires were connected to the bulb.” The teacher thanks him for sharing. The episode continues with the students sharing their predictions and is truncated here for apparent redundancy.

Analysis of this video segment reveals that, as in the first Initial Ideas video discussed above from the chapter on Force and Interactions, the students offered their ideas and supported them with logical reasoning. The students’ predictions and their supporting explanations range from scientifically inaccurate to accurate, as shown in Table 6.3. Regardless of the accuracy of students’ ideas, the teacher offers nearly identical responses, remarking, “interesting” and thanking the students for sharing. The teacher’s choice to change the structure of the activity due to time considerations (as compared to the Initial Ideas in Force and Interactions) did not change her approach of avoiding evaluation of students’ ideas.

Table 6.3. Students' initial ideas for C5A1

Student	Configuration	Statement	Idea
Craig		No. “Well, because the negative is the ground, which has to touch the side of the bulb, which is the ground. And the positive has to come to the bottom of the light bulb to light—to, uh, transfer the electricity.”	Probably recognizes that there is no path through the bulb.
Sonia		No. “Because um, we need the positive and the negative um charge to make something work. So, if you want to make the light bulb light you would have to make it touch the wire because that's where the negative and positive come together.”	Negative and positive must meet (“clashing currents”).
Malcom		Yes. “The bulb is touching the negative part of the battery, and the wire is going from the positive part of the um, metal part of uh [inaudible].”	Probably recognizes path through the bulb.
Sonia		No. “Because um...the wire has to touch the negative part... Um, the negative side of the battery.”	Thinks the wire needs to directly contact the negative pole of the battery.
Craig		No. “Because the bulb's not grounded, and it has to make a complete...because they're both hooked up to the one spot, and it has to be--well I think--it has to be grounded by the side of the bulb and the hot wire goes into the bottom of the bulb. But if they're both touching in one spot it can short out the circuit.”	Recognizes that there is no path through the bulb.
John		Yes. We said because the wires were connected to the bulb.	Thinks it will light because both wires are contacting the bulb.

Observation: In this Initial Ideas activity the students share a range of ideas of varying degrees of scientific accuracy.

Observation: In this Initial Ideas activity the teacher refrains from making any evaluative statements about students' ideas.

Collecting and Interpreting Evidence

The *Collecting and Interpreting Evidence* (C&I) activities follow directly after the Initial Ideas activities. According to the PET Teachers Guide, the C&I activities are designed for students to collect and use the evidence from laboratory experiments, demonstrations, and computer simulations to construct the target ideas of the respective chapters. Students are expected to follow the instructions that they are provided in each activity and to work with their lab groups to seek answers to the provided questions. The video selected for analysis here was taken at the start of Chapter 5, Electric Circuit Interactions, and the handout for the activity can be found in Appendix B.

Background

In the previous section, students expressed their initial ideas by making and sharing predictions about whether or not each of the six arrangements of a light bulb, a battery, and a wire will light the bulb. This video segment begins with the students engaging in *Experiment 1: What conditions are necessary to light the bulb?* This activity is designed to allow students to test their initial ideas and to help students determine how the components of a simple circuit can be connected to light the bulb. In this activity, the students experimented with the real apparatus to test their predictions from the Initial Ideas activity and addressed the following guiding questions:

Guiding Questions:

- Which part or parts of the battery need to be part of the connections?
- Which part or parts of the bulb must be touched to make the bulb light?
- How do the two ends of the battery need to be connected to the two sides of the bulb?

Figure 6.11. Guiding Questions Chapter 5, Experiment 1.

After experimenting with each of the configurations in Figure 6.8, students should conclude that the bulb must make contact with the positive and negative ends of the battery (either directly or through a wire), and that the bulb must be touched on the side by one pole of the battery and on the bottom by the other pole so that electricity can flow in one direction, as shown in Figure 6.12.

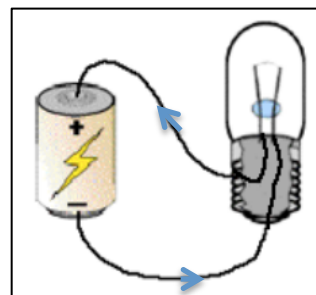


Figure 3.12. Connecting a light bulb.

After completing *Experiment 1*, the students conducted *Experiment 2*:

How do the two ends of the battery need to be connected to the two sides of the bulb? and address the question:

Guiding Question:

Do the two sides of the bulb need to be connected to the positive and negative ends of the same battery?

Figure 6.13 Guiding question Chapter 5, Experiment 2.

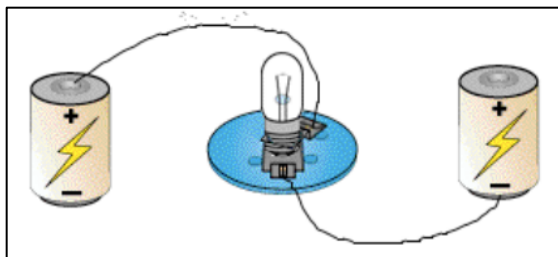


Figure 6.14. Experiment 2

Students are provided with Figure 6.14 and instructed to test it to help them answer the question above. Recall that in the previous experiment students have determined how the bulb must be connected and that the bulb must be electrically connected to the two poles of the battery.

The goal of Experiment 2 is that the students infer one of the central principles of circuit theory: *electrical current will only flow if the path of current makes a closed loop, or circuit*. As stated above, students tested six different bulb, battery, and wire configurations and determined that configurations 2, 4, and 6 light while the others do not. Though the path through the bulb and the connection of the bulb to the poles of the battery are typically understood after testing these six configurations and answering the associated questions, the video evidence suggests that students had yet to understand that a complete loop must be made for electrical current to flow.

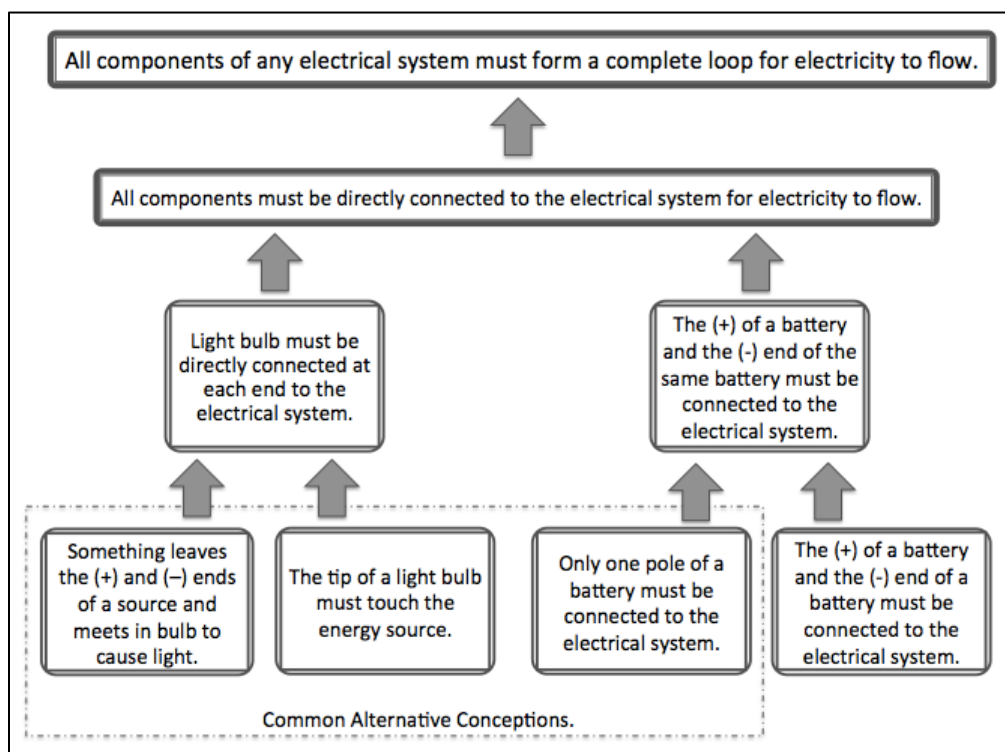


Figure 6.15. A proposed trajectory toward the general circuit principle.

It is common for students to think that only positive and negative, not necessarily from the same battery, are required for electricity to flow (Goldberg, Otero, Robinson, 2010). The testing of the two-battery configuration in Figure 6.14 is designed to provide the evidence students need to infer what I refer to here as the *circuit principle*. An approximation of a typical student trajectory toward inferring this principle is presented above in Figure 6.15.

Analysis of Video 3, Part I – How do students engage in this Collecting and Interpreting Evidence task?

In the previous two analyses of Initial Ideas activities, the focus was on the overall classroom culture, the nature of student engagement, and on the nature of teacher facilitation. For this analysis, we focus in on the activity of one lab group. This video shows the students conducting *Experiment 1: What conditions are necessary to light the bulb?* and then conducting *Experiment 2: How do the two ends of the battery need to be connected to the two sides of the bulb?* This is a lab group of four. Manuel is seated on Sonia's left and they are both on one side of the lab table with their backs to the camera. Dion is seated directly across from Manuel, and Tina across from Sonia, as shown in Figure 6.16.

Manuel could be considered the clown of the group, often joking and poking fun at others. His family travels to Mexico often and had left this school by the end of the year. Dion is an easy-going student with a pretty quiet demeanor. He works hard and is well liked. Tina is by the far the most quiet of the group. In an interview she stated that she just likes to "sit back and watch."

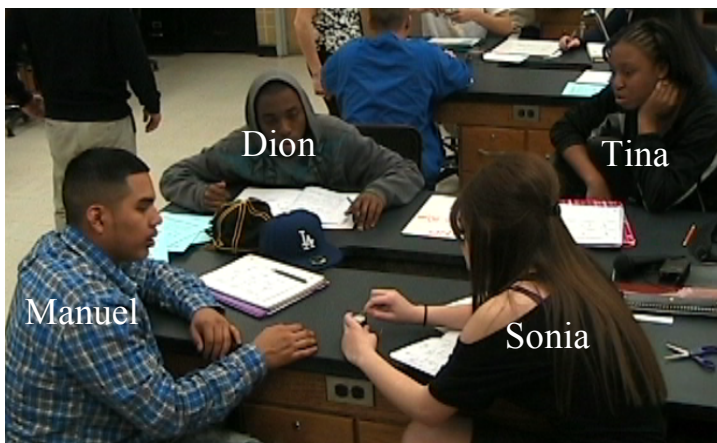


Figure 6.16. Lab group

Sonia is a model student, nearly always completing her work on time and setting high goals for herself. She is a quiet leader among the group, and has expressed in interviews that she never liked science before but it had become her favorite subject. She is undocumented and has expressed consternation about what her academic future may hold.

This video excerpt begins with the students already having picked up a battery, and two bare copper wires.

- 1 [Researcher places a small light bulb on this lab group's table. Manuel picks it up and examines it]
- 2 **Manuel:** This is like for a car. [Dion looks at the bulb Manuel is holding]. You see that wire in the middle?
- 3 [Sonia is manipulating the battery and wire]
- 4 **Manuel:** Does it do anything or what?
- 5 **Sonia:** I think it's getting hotter. The wire.
- 6 **Manuel:** What?
- 7 **Sonia:** Is it me or is it?
- 8 **Manuel:** What are you talking about?
- 9 **Sonia:** The wire. I thought it was getting hotter.
- 10 **Manuel:** Stupid, it's passing electricity to it. It's copper.
- 11 **Tina:** Put the light bulb up there.
- 12 **Manuel:** Is it getting hot? Either [inaudible]
- 13 **Sonia:** [inaudible] You try it. I didn't get it.
- 14 **Manuel:** [Manuel grabs the wire and feels it] Yeah it is.

The students begin by examining and playing with the equipment. Manuel remarks that the bulb looks like one he has seen used in a car. Though not in the lab instructions, Sonia connects the ends of one wire to the two poles of the battery. Because there is very little resistance in the wire, this short-circuiting causes electricity to flow unimpeded, causing the wire to heat up. Sonia is surprised to observe this. Tina suggests they put the bulb on top in line 11, and Manuel confirms the heating effect in line 14.

Sonia gets the group on task in line 15 below by starting to test configuration number one.

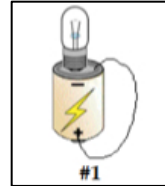
- 15 **Sonia:** [Takes the wire back] Let's try this. Alright check it out. [touches wire to the bottom of the battery and other end of the wire to top]

16 **Manuel:** Bottom one?

17 **Dion:** Yeah, positive on the bottom.

18 **Sonia:** Now put the light bulb on.

19 **Manuel:** Where? Just on top? [Manuel places the bulb on top of the battery. Failure. [The group records the result on their handouts]



The group observes that the bulb does not light, and records it in their notebooks. They move on to configuration two.

20 **Sonia:** Alright. Next. So, the side. [Sonia and Manuel work together to set up #2].

21 **Manuel:** No, the wire's touching the bulb. Ah! [Manuel drops the bulb onto the table]

22 **Sonia:** Oh! Don't break it.

23 **Manuel:** It's not broken, don't worry.

24 **Sonia:** No, I was like checking if there was like a hole in the light bulb.

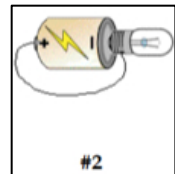
25 **Manuel:** Whoooo! [The bulb lights] Nice.

26 **Dion:** It's like dirty money. [The group records the observation]

27 **Manuel:** Yes, I was right! [Dion smiles and looks up at Manuel. Manuel makes a two-handed obscene gesture to Dion] Fuck you!

28 **Sonia:** Alright.

29 **Manuel:** Hu-hu [Laughs]...Yes! [Pumps fist]



The group connects configuration two, and is excited to see the bulb light. Manuel hoots and says, “nice” in line 25 above, and Dion makes an expression, “dirty money” I am unfamiliar with in line 26. This may be a positive expression similar to “money,” a slang word often used to indicate that something is of high quality. Manuel then remarks that he “was right!” in line 27, sparking some playful gesturing between he and Dion. Again, in line 29, Manuel laughs, pumps his fist, and exclaims, “yes!”

The group moves on to configuration three.

30 **Manuel:** Maybe we'll touch the [inaudible].

31 **Sonia:** OK well. Grab those. Grab this. [Hands the ends of two strands of wire to Manuel. They connect configuration 3].

32 **Dion:** No.

33 **Sonia:** What?

34 **Manuel:** Nope. Failure.

35 **Sonia:** For number three?

36 **Manuel:** Yeah....Number four. [Sonia and Manuel connect #4]

37 **Manuel:** Touchin' uh, the other metal.

38 **Sonia:** [Bulb flashes on and off quickly] Oh, it does. Did you see it?

39 **Manuel:** There it is. We got light! [The group records the observation]

40 **Manuel:** [Grabs the apparatus] Now. [Says something in Spanish]

41 **Sonia:** Wait. Did you do that one? [Points to diagram of configuration #4]

42 **Manuel:** Four?

43 **Sonia:** Yeah. We're on number five aren't we?

44 **Manuel:** Yeah, that's right. That's what I'm trying to do.

45 **Sonia:** What are you trying to do? We're on five.

46 **Manuel:** Five. That's what I'm tryin' to do! [Sonia laughs] Oh, it looks like that.

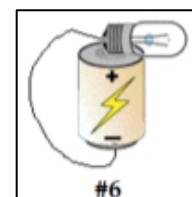
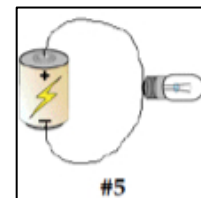
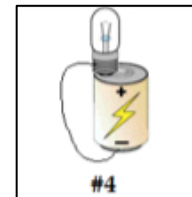
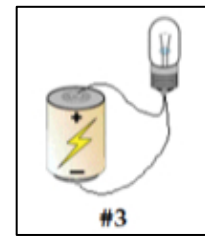
47 **Teacher:** [Walks up and leans in]. Anything?

48 **Dion:** Do we need two of those, 'cause [inaudible]? [points to diagram #5]

49 **Sonia:** Alright. Try it again. Try it again. [Manuel and Sonia connect #5 again. It does not light] Hold on.

50 **Manuel:** Nada. Nothing. No. [The group records the observation]

51 **Manuel:** [Sonia and Manuel connect #6; it lights] Oohh, look at [inaudible]. Damn!



- 52 **Sonia:** We like failed. [Laughs]
- 53 **Manuel:** I didn't. I got like two of them right so...[Gestures hands like firing guns] I'm just a beast like that. You know what I'm sayin'?
- 54 **Sonia:** No, you just guessed.
- 55 **Manuel:** No, I didn't.
- 56 **Sonia:** Yes, yes, yes, yes.

In the segment above, the group moves through the remaining four configurations, making observations and recording them. When they are finished, Sonia remarks, “we like failed,” in line 52 above. Manuel playfully claims success at getting two of the six predictions correct. The teacher then gives instructions for the remaining time left in the class.

- 57 **Teacher:** [To the entire class] So, hey you guys, we have five minutes. We're gonna debrief, and here's how we're gonna do it. Actually, a couple things. First, you have an exit ticket, but it's a group exit ticket. You're going to do it on the whiteboard, so you need to answer this question: How do you need to connect the wire or wires, battery, and bulb for it to light up? You could draw a picture if you wanted. You have two minutes to do that.
- [The groups get to work]
- 58 [Tina starts writing on the whiteboard. There is no discussion in this group]
- 59 [Tina taps on the whiteboard with the marker] Pssst. [Looks at Sonia and points to the whiteboard. Sonia holds her hand out and Tina hands her the whiteboard and marker. Sonia starts writing on the whiteboard]
- 60 **Teacher:** Alright, here's what we're going to do for the last three minutes. We're going to share our boards. So, as a debrief...um...I wanna know what you know about how you need to connect the bulb, the battery, and the wire to see it light up. So, let's start and we'll just go really quickly. What I want you to do is show your board and share your thinking. What did you learn from today's lab. And I'll come around and pick up your marker and eraser. Let's start with group number one. Give them your attention please.

61 **Sonia:** [Finishes writing and whispers quietly to her group] I don't know. [Puts down the marker and whiteboard]

In the episode above, as the lab group prepares their whiteboard for sharing, they show some uncertainty in what they have found in Experiment 1. Tina attempts to write an explanation on the whiteboard in line 58, becomes discouraged and gestures to Sonia for help in line 59. Sonia takes on the task, but whispers, “I don’t know,” as she finishes writing her explanation. Craig begins to share his group’s answer below.

62 **Craig:** Well, we said you need to connect it where it's almost like a circle and the positives and negatives can't touch or else it'll short out the circuit.

63 **Teacher:** Thank you very much. Complete circle. You have to have some kind of complete circle. Thank you for sharing. Group number two will you share?

64 **Dion:** [Reading whiteboard Tina is holding up]. There has to be a con...nection between the negative and positive input and has to connect to the light bulb.

65 **Teacher:** Alright. So, there has to be some connection between the negative and the positive and it has to touch the light bulb. Thank you. Go ahead, group number three. Shhh. Alright, we don't have much time Let' share every group share. Group number three.

66 **Malcom:** The negative has to touch the bottom of the bulb and the positive has to touch the side or vice versa in a circle (gestures a circle).

The groups then begin to share the findings from their experiment. The three groups above offer a variety of explanations. In line 62, Craig remarks that the “positive and negatives can’t touch,” and mentions a circle. Dion explains that “there has to be a connection between the negative and the positive and has to connect to the bulb in line 64. In line 64, Malcom explains that the bulb must be connected on the bottom and the side “in a circle.” Two of the students above mention a circle. The discussion continues.

- 67 **Teacher:** Interesting. I'm seeing a lot of building on one another here. Nice addition of information. So, think about it needing to touch the bottom of the bulb and the side of the bulb. Interesting. Thank you very much. Group four, go ahead and share.
- 68 **Lisa:** To make the light bulb light you're touching the wire touching the positive or negative side of the light bulb and touching the light bulb wrap-around or on the opposite side of the wire.
- 69 **Teacher:** Interesting. Thank you very much for sharing. Group number five.
- 70 **John:** We said the wire has to somehow be touching the bottom of the bulb.
- 71 **Teacher:** The wire needs to touch the bottom of the light bulb.
[James adds something inaudible to the answer]. Ok, the little nub on the bottom. OK. Hey guys, let's be super quiet so we can hear this group. [James again says something that is inaudible]. Thank you very much. Alright. Last, but not least, group six.
- 72 **Kevin:** We just said the wire has to touch both sides and the bulb.
- 73 **Teacher:** So, wire needs to be touching the bulb and the battery in two places. I think that's what we're walking away with. [Housekeeping announcements end the class]

Above, three more groups offer answers consistent with those already shared. The teacher summarizes the relevant finding that the “wire needs to be touching the bulb and battery in two places” above in line 73. Although some of the students’ answers don’t seem to reflect this, time marches on, and the teacher must wrap things up before the bell. The students have nearly completed Experiment 1, and will start Experiment 2 the next day.

Class begins the next day with students completing questions from Experiment 1. Recall The goal of Experiment 2 is that the students infer one of the central principles of circuit theory: *electrical current will only flow if the path of current makes a closed loop, or circuit*. Though the path through the bulb and the connection of the bulb to the poles of the battery are typically understood after testing these

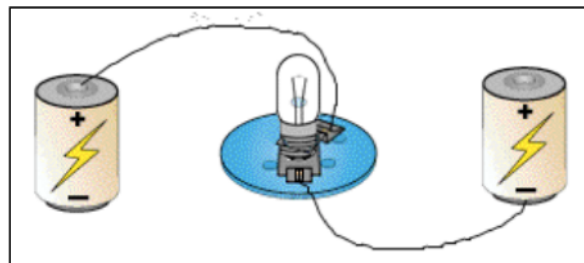


Figure 6.14. Experiment 2 (Shown previously).

six configurations and answering the associated questions, the video evidence suggests that students had yet to understand that a complete loop must be made for electrical current to flow. The testing of the two-battery configuration in Figure 6.14 is designed to provide the evidence students need to infer what I refer to here as the *circuit principle*. Tina is not here for this activity, as shown in Figure 6.17.

- 1 **Dion:** And what does question 8 say,
Manuel?
- 2 **Manuel:** [Reading from his paper]
Which part of parts of the battery need
to be part of the connections?

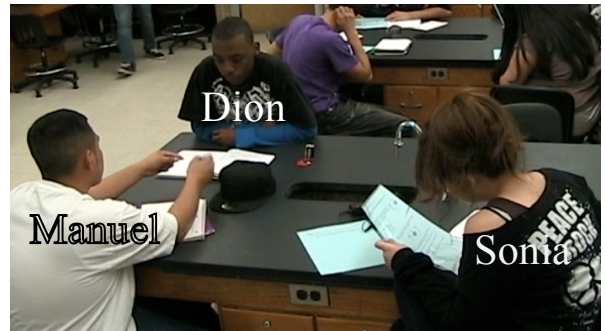


Figure 6.17. Lab group II.

- 3 **Manuel:** [Looks at Dion]. Like, like which part...[Sonia grabs handout and starts reading
it] which part of the battery needs to be like part of...let's say like the positive. Let's say
you have the battery, right?
- 4 **Dion:** Yeah.
- 4 **Manuel:** The positive is like, is touching like the bottom of the bulb and the negative wire
is touching...
- 5 **Dion:** The side?
- 6 **Manuel:** Like the side or something. Or like how do you think it needs to be, you know?
- 7 **Dion:** Oh, the arrangement.

Lines 1-7 above show Dion and Manuel are finishing up the questions from Experiment 1. Dion asks Manuel what question #8 is, and Manuel reads the question. Manuel continues in lines 2 and 4 to explain the meaning of the question, and in line 7 Dion appears to understand that the question is asking how each of the individual components should be configured in order for the bulb to light. Sonia appears to have already answered the question Manuel and Dion are discussing and has begun to read the instructions for Experiment 2. Below, she makes a move to get the equipment and start the experiment.

- 8 **Sonia:** Let me see that [Sonia points to battery and bulb; Dion hands them to her].

- 9 **Manuel:** Why do you getta do it? I wanna do it.
- 10 **Sonia:** You didn't ask [inaudible].
- 11 **Manuel:** You didn't ask either.
- 12 **Sonia:** Yes, I did. That's why I was like, "can you give me that?"
- 13 **Manuel:** No, you didn't
- 14 **Sonia:** Come here. Help me.
- 15 **Manuel:** 'cause I thought you were [inaudible].
- 16 **Sonia:** Help me! (growing impatient) [Manuel and Sonia begin manipulating the materials]

In line 8 above, Sonia asks for and gets the apparatus. Manuel immediately begins to complain in Line 9 that he wants to be the one in control of the apparatus saying, "Why do you getta do it? I wanna do it." Though Manuel is insistent that he wants to manipulate the equipment, Sonia states in lines 14 that Manuel is welcome to help her. Manuel continues to complain, and in line 16, Sonia grows impatient and raises her voice to Manuel. The exchange ends with Sonia in primary control of the apparatus. Note that while Manuel and Sonia appear eager to experiment with equipment, Dion makes no move to do so.

Manuel and Sonia begin to experiment with the equipment. In the segment below, Manuel and Sonia are cooperating to connect the configuration shown in Figure 6.14 while Dion looks on.

- 20 **Sonia:** Alright...You get that one
[Sonia places one of the two batteries
in front of Manuel]. I get this one.
- 21 **Manuel:** Are you touching negative?
- 22 **Sonia:** Yeah, I'm [inaudible]. [Sonia
continues tinkering while Manuel and
Dion watch. The light does not light.]
- 24 **Manuel:** How about we change it? I do negative, you do positive. [Dion looks on as his lab partners experiment]

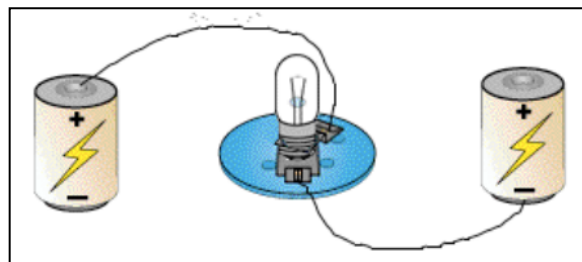


Figure 6.14. Experiment 2 (Shown previously).

- 25 **Manuel:** What the fuck?! [Manuel drops the equipment and turns away from the task.
Sonia continues tinkering, and Dion leans in and turns the handout that is laying on the
table towards him. About 10 seconds after disengaging the task, Manuel turns back toward
Sonia and looks at the handout. The teacher walks up to the table and begins watching and
listening.]
- 26 **Sonia:** Wait, let's try it again. [Manuel touches the wire coming off one side of the bulb
and places it on the positive terminal of the battery]
- 27 **Sonia:** You're doing the positive, you idiot! [laughs]
- 28 **Manuel:** Oh. Ah! It (the wire) came out! [Manuel stands and continues to help. Sonia
continues tinkering. The teacher comes around the table across from Sonia to get a closer
look at what the students are doing. Again, the light does not light.]
- 29 **Teacher:** Is that what you expected?
- 30 **Sonia:** I was expecting it to light. Um, not gonna work.

In line 24, upon seeing that the configuration did not light the bulb, Manuel suggests that he and Sonia each switch their wires to the opposite pole of the battery that each is holding. They each switch to the opposite pole of their respective batteries, and the bulb does not light. Manuel shows strong emotion in line 25, expressing frustration with their lack of success by cursing and throwing the equipment he is tinkering with onto the table. He then turns away from the task and his lab partners. As will be shown below, Manuel thought this set-up should light the bulb. His statements indicate that he does not yet understand that the bulb must be connect on both ends to the *same* battery, suggesting a “clashing currents” model, one representation of which is shown in Figure 6.14. However, the evidence before him contradicts his mental model and his associated expectations for success in lighting the bulb. Manuel’s expressions of frustration suggest that he is experiencing strong emotions. Based on his emotional response, it is plausible to assert that he is heavily invested in this activity. Sonia continues to experiment while Manuel disengages from the activity, and Dion appears to become more interested in the experiment while Manuel is disengaged. After a short break, Manuel returns and immediately re-engages the activity.

Observation: Manuel is intensely interested and engaged in this task, so much so that he has an intense emotional reaction when the laboratory evidence does not align with his current conceptual model. And though he experiences frustration, curses, and disengages from the task momentarily, he returns to it and persists.

At this point, the teacher makes some more direct pedagogical moves, asking in line 31 below what the difference is between the current configuration and one in which the components are part of a complete circuit.

- 31 **Teacher:** That's interesting because here [as shown in Figure 6.17 below, the teacher points to the diagram shown on the right] it's going from a positive to a negative and you set it up to go to a positive to a negative. So what's the difference between what you set up in this one or this picture?

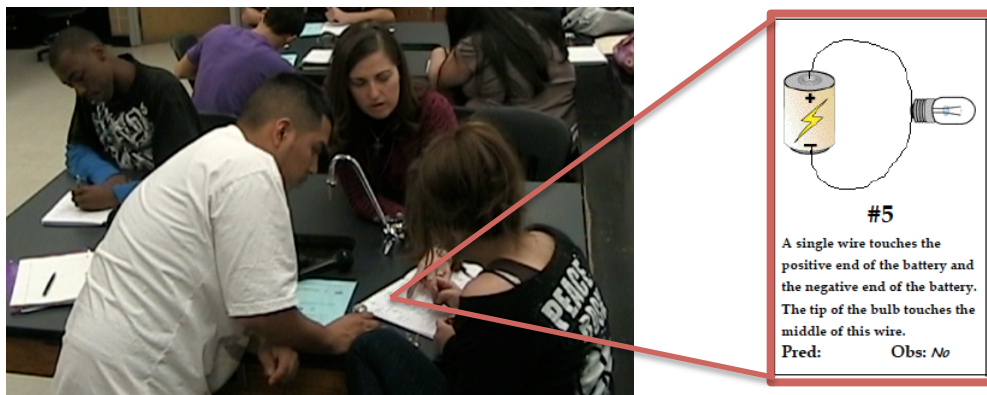


Figure 6.18. The teacher pointing to a circuit diagram.

Note: Figure 6.18 does not show a completed circuit (as Figure 6.12 does), because the wires are not touching the bulb correctly. It was likely that the teacher needed some pedagogical tool immediately and quickly chose this one to encourage the group to consider the loop configuration.

- 32 **Manuel:** Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know? And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that (points to something on the apparatus that is hidden from the camera).
- 33 **Teacher:** Interesting.

- 34 **Manuel:** And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up. [Other students are toggling the overhead lights, presumably so that they can see if their bulbs are equally bright.]
- 35 **Teacher:** Interesting, so you have... So, yeah, that's really interesting. How? You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said "check." Alright, it's going from the positive end of one to the negative end of another, but it's still not working. So, what's the difference between what you set up here with these two batteries and like...
- 36 **Sonia:** The wires aren't directly touching the light bulb.
- 37 **Teacher:** OK, the wires aren't directly touching the light bulb. Do you wanna try it by taking the wires out and have...

[Dion and Teacher have a short conversation about other ways to connect the wires. The students take the bulb out of the holder, hold the wires manually to the bulb, and observe that the bulb did not light.]

- 48 **Sonia:** Alright.

In line 31 above, the teacher, in need of a pedagogical tool to facilitate the students' reasoning, attempts to draw the students' attention to the loop in Figure 6.18. Manuel appears to still be confounded by the failure of the bulb to light in this configuration as evidenced by his explanations of why the bulb should have lit in lines 32 and 34. In line 35, the teacher walks the students through their current conceptual model, confirming Manuel's assertions that the wires are, in fact, connected correctly to the bulb. Again, she draws the students' attention to the diagram and asks what the difference is between it and the present set-up. In an effort to determine why the bulb won't light, Sonia suggests in line 36 that the wires must be touching the bulb. As shown in Figure 6.14 above, the bulb is in a holder (to make the apparatus easier to work with), but the wires are in direct *electrical* contact with the bulb. That is, the wires are connected to the bulb through a conductor. In line 48 above, the students connect the wires directly to the bulb, and it does not light.

At this point there is nothing in the transcript data that suggests that the students in this lab group have inferred the general circuit principle discussed above and strong evidence that they have not. They have connected the wires to the bulb correctly, both with and without the bulb holder, and have the bulb connected to the opposite poles of two *different* batteries. Yet it is clear that they are perplexed by the failure of the bulb to light, and thus have not yet realized that the components must form a complete circuit. The transcript presented and analyzed thus far suggests that they have determined that in order for the bulb to light:

1. there must be a path through the bulb (in lines 32 and 34, Manuel describes the points of contact that complete the flow of current through the bulb); and
2. that the bulb must be connected to the positive and negative ends of one or more batteries (this is not specific enough, because the bulb must be connected to the poles of the *same* battery), as evidenced in lines 20-30 which concludes with Sonia stating that she was “expecting it (Figure 6.14) to light.”

It appears that the teacher recognizes that the students understand points 1 and 2 above as she walks the students through their current conceptual model in line 35. The teacher continues below making explicit pedagogical moves to guide student reasoning.

- 49 **Teacher:** Huh. So, here's my question for you: What's the difference between what you have going on here in this picture...
- 50 **Sonia:** Oh, this one isn't touching...the light bulb isn't touching the battery.
- 51 **Teacher:** That's true. So, that's a difference from here. And look at these two different pictures. We have this picture with one battery going from the plus to the minus (See upper Figure 11). And then this one (bulb goes from bulb to +terminal of one battery and to -terminal of another battery, shown in lower Figure 6.19).

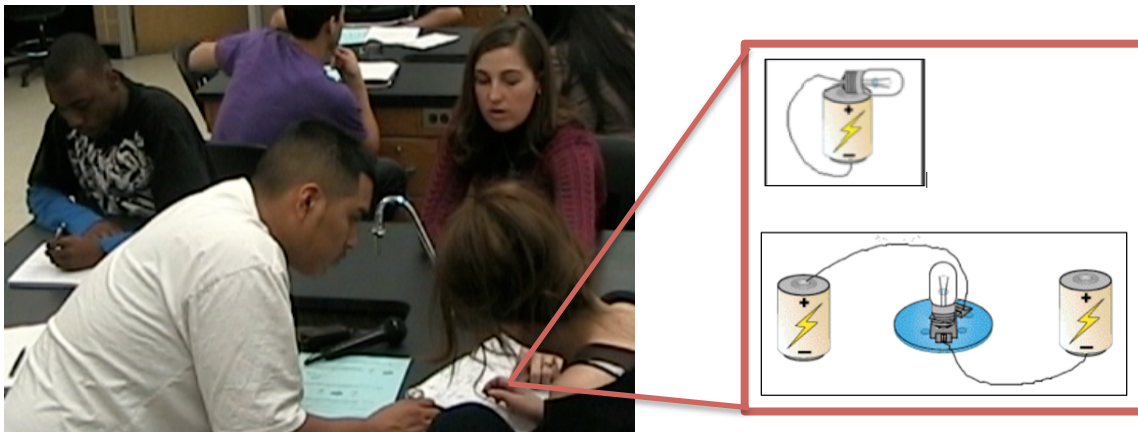


Figure 6.19. Teacher attempting to draw students' attention to differences.

- 52 **Sonia:** Oh.
- 53 **Teacher:** What's the difference between those two set-ups that you made?
- 54 **Sonia:** There's two batteries.
- 55 **Teacher:** So, this one has two batteries.
- 56 **Sonia:** It's not getting the whole circuit.
- 57 **Teacher:** What do you mean when you say circuit?
- 58 **Sonia:** It's supposed to make like, like it's a circle of life [traces a circle on the paper with her finger].
- 59 **Teacher:** Oh, interesting. That's interesting.

The teacher again draws the students' attention to a diagram in which the components are connected in a completed loop (upper diagram in Figure 6.19 showing a correct configuration) and asks what the difference is between that diagram and the lower one in Figure 6.19. She does this twice above, once in line 49 and then again in line 53. In line 50, Sonia recognizes another inconsequential difference in one of the diagrams showing the bulb touching the top of a battery. She recognizes yet another inconsequential difference in line 55, where she points out that the current physical apparatus has two batteries. Though neither of these differences relate to whether or not the bulb will light, the latter difference appears to trigger a revelation. Sonia recognizes the significant difference in line 56—that the components do not form a circuit. She continues her explanation below.

- 60 **Sonia:** That's how you're supposed to...There supposed to connect each other and, like, either these have to be touching like that [puts batteries in series (stacked end to end)] and then one wire would have to come from here and the other one from here (the top of the top battery) and then connect to this (the bottom of the bottom battery) and that would probably...
- 61 **Teacher:** You wanna try?
- 62 **Sonia:** Yeah.
- 63 **Teacher:** OK. So, you just found a key difference and I'm...so let's double test...let's double-check that we could still do it with two batteries as you propose in your method. And then we'll see if it has to be in a circle.
- 64 **Sonia:** I think it does because if it doesn't there's no circuit.
- 65 **Teacher:** Ah. So, you're saying for there to be a circuit, there has to be a circle.
- 66 **Sonia:** Yeah.
- 67 **Teacher:** Hm. Interesting. So, is this a circuit? [points to simple circuit in Figure 9]
- 68 **Sonia:** Yes.
- 69 **Teacher:** And then... [points to two battery setup in Figure 6.14]
- 70 **Sonia:** No.

Sonia continues her explanation of the *circuit principle* in line 60 above, and the teacher asks if the students want to test it. In line 63, the teacher begins to tell the group that they “just found a key difference,” but stops herself and resumes encouraging the group to test their hypothesis. Below, the teacher suggests that they test it with both batteries in series (connected end to end).

- 71 **Teacher:** Alright, let's try it with double battery.
- 72 **Sonia:** OK. Are those touching? [Sonia works with Manuel to hold the set-up. Dion looks on. The bulb lights.]
- 73 **Sonia:** Ha!

- 74 **Teacher:** Ah, and what do you notice about that bulb compared to when you do it with one battery?
- 75 **Sonia:** It's um...
- 76 **Dion:** It's a lot brighter.
- 77 **Teacher:** It's brighter. Interesting. So, you just discovered a key compon...a key thing about electricity.
- 78 **Sonia:** Ding, ding, ding [intermittently lights circuit (imitating a win on a game show. All three kids laugh at the "ding" joke. Teacher leaves the group.)]
- 79 **Manuel:** Nice!
- 80 **Sonia:** Yeah, high five [hi-fives Manuel then Dion] Uh! [emphatic] You better help me find this out [laughs].
- 81 **Manuel:** Nice!

In line 72 above, the group tests it and the bulb lights. In line 78, Sonia playfully makes a “ding, ding, ding” sound and intermittently lights the bulb in sync with the sounds as if they are the winners on a game show. In line 79-81, the group erupts in celebration at their success, Manuel emphatically compliments the group’s work, and all three engage in hi-fives.

Observation: *These students were guided by curriculum and teacher through the processes of scientific induction.*

Observation: *The students appear to enjoy engaging in scientific induction. When they realize that they have developed a key scientific finding in lines 78-81, they take great pleasure in it.*

The episode above represents a principal event in science learning—*scientific induction*. After making predictions, examining and testing various configurations of the apparatus, and becoming frustrated and perplexed in their attempts to understand a physical phenomenon, Sonia and her lab group infer a general principle of electricity through inductive, evidence-based reasoning. This episode of scientific induction was heavily guided by the expertise embedded in the curriculum and the teacher’s

strategic pedagogical moves. Yet it is clear that under these conditions, moving inferentially from concrete instances of physical phenomena to a general principle is something that is both within the grasp of these students and something that they appear to thoroughly enjoy, as evidenced by the compliments, emphatic expressions of success, and gestures and physical contact in lines 78-81 and shown in Figure 6.20.



Figure 6.20. Students celebrating successful induction of the circuit principle.

It is important to note that the students are doing the same thing at the end of this activity as they did at the beginning. In Experiment 1, they tested six different configurations. Some lit the bulb, and some did not. At the end of Experiment 2, they are simply lighting a bulb with batteries, a bulb and a wire. The key difference in Experiment 2 is that they have not just lit a bulb, they have extracted a general physical principle. Of course, this episode of scientific induction was heavily guided by the curricular tools and by the expertise teacher. Yet, it appears that, to the students, they have discovered something previously unknown. The data suggest that this principle was previously unknown to them, and it is clear that the development of this widely accepted scientific principle for themselves is something they enjoyed very much.

It is important to note that this analysis takes the lab group as a unit of analysis. This is an analytical decision in which the researcher must acknowledge that it is highly probable that differences in individuals' learning/cognition occur when learning is organized as such to be highly collaborative. It is unclear whether or not the student who first inferred the general circuit principle may have made this inference were she working on her own, nor is it clear when or if the other two members of the lab group

inferred this principle. Nonetheless, all of these students participated in the developing of an inference through a shared experience.

Analysis of Video 3, Part II – How does the teacher facilitate learning in this CIE task?

The Collecting and Interpreting Evidence video segment from the previous section was again analyzed to determine how the teacher facilitates student learning. Specifically, what pedagogical moves does the teacher make to guide student sense-making and inductive reasoning? The analysis is summarized below in Table 6.4. The full analysis can be found in Appendix C.

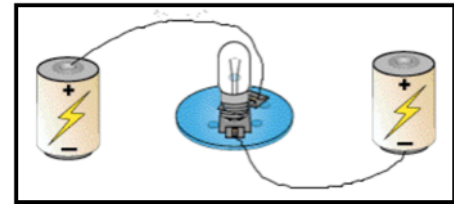


Figure 6.14. Experiment 2 (Previously shown).

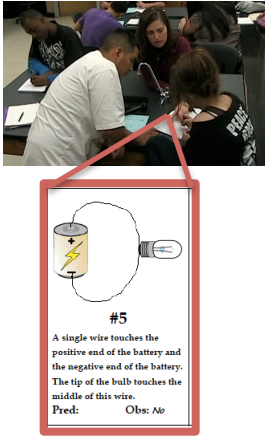
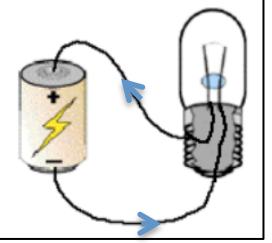
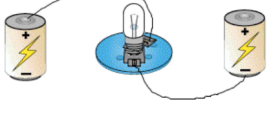
In this episode we see that the teacher uses three distinct pedagogical strategies to guide the students through scientific induction. These strategies are:

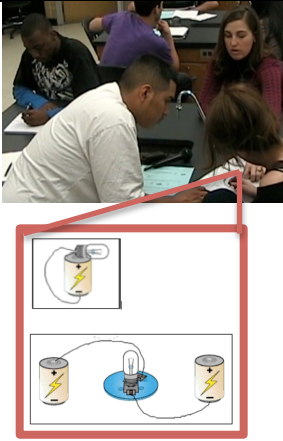
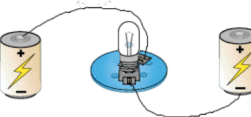
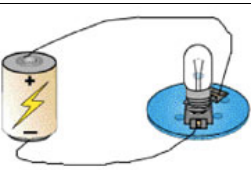
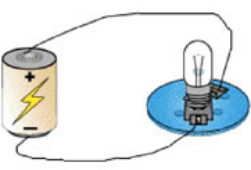
1. Making benign comments that appear to affirm students' attempts to observe, infer, and explain, such as "interesting" and "thank you," without evaluating the students' ideas or explanations.
2. Employing in the moment pedagogical strategies and tools, such as explicitly drawing students' attention to differences in apparatus configurations and associated observations with the intent of helping them develop accurate explanations.
3. Deferring to the available laboratory evidence to determine the validity of students' ideas and explanations by encouraging students to test their assertions.

The teacher appears to interfere with student sense-making very little, responding to students' assertions, accurate and not, as "interesting. She defers to laboratory evidence to sanction students' ideas (though not completely, as shown in line 63) and simply notes that students' ideas are "interesting." However, when she sees students not progressing, she quickly finds pedagogical tools in the classroom and employs the pedagogical move of drawing students' attention differences in apparatus configurations. When they recognize the answer, she suggests that they test it, thus deferring to students use of laboratory evidence to sanction new knowledge in the classroom. The condensed analysis is provided below in Table

6.4. This condensed analysis provides transcript excerpts in the left column, graphical aids to help the reader understand the subject matter context in the middle, and descriptions of teacher moves in the right column. The full analysis is provided in Appendix C.

Table 6.4. Summary of analysis of teachers' pedagogical moves.

Transcript Excerpt	Graphic	Teacher Moves
29 Teacher: Is that what you expected? [to Sonia] 30 Sonia: I was expecting it to light. Um, not gonna work. 31 Teacher: That's interesting because here [the teacher points to the diagram shown on the right] it's going from a positive to a negative and you set it up to go to a positive to a negative. So what's the difference between what like you set-up in this one or this picture?		Making benign comment (“that’s interesting”) that appears to affirm students’ attempts to observe, infer, and explain without evaluating the students’ ideas or explanations. In the moment, the teacher recognizes the need for a pedagogical tool. In this case, the teacher needs a circle and finds one on the student’s paper. She uses it to draw students’ attention to difference configurations.
32 Manuel: Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know? And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that. 33 Teacher: Interesting. 34 Manuel: And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up. 35 Teacher: Interesting, so you have... So, yeah, that's really interesting. How? You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said "check." Alright, it's going from the positive end of one to the negative end of another, but it's still not working. So, what's the difference between what you set up here with these two batteries and like...		Makes benign comments (“interesting”). Confirming and re-voicing students’ helpful ideas Uses a diagram as pedagogical tool. Draws students’ attention to differences in configurations.
36 Sonia: The wires aren't directly touching the light bulb. 37 Teacher: OK, the wires aren't directly touching the light bulb. Do you wanna try it by taking the wires out and have...[Students try taking the wires out.]		Defers to students’ use of evidence to sanction ideas (“Do you wanna try it...?”)

49 Teacher: Huh. So, here's my question for you: What's the difference between what you have going on here in this picture... 50 Sonia: Oh, this one isn't touching...the light bulb isn't touching the battery. 51 Teacher: That's true. So, that's a difference from here. And look at these two different pictures. We have this picture with one battery going from the plus to the minus. And then this one (bulb goes from bulb to +terminal of one battery and to - terminal of another battery, shown in lower Figure 4.14) ... 52 Sonia: Oh. 53 Teacher: What's the difference between those two set-ups that you made?		Uses a diagram as pedagogical tool. Draws students' attention to differences in configurations.
Transcript Excerpt	Graphic	Teacher Moves
56 Sonia: It's not getting the whole circuit. 57 Teacher: What do you mean when you say circuit? 58 Sonia: It's supposed to make like, like it's a circle of life [traces a circle on the paper with her finger]. 59 Teacher: Oh, interesting. That's interesting.		Makes benign comments ("interesting").
60 Sonia: That's how you're supposed to...There supposed to connect each other and, like, either these have to be touching like that [puts batteries in series stacked end to end] and then one wire would have to come from here and the other one from here and then connect to this and that would probably... 61 Teacher: You wanna try? 62 Sonia: Yeah. 63 Teacher: OK. So, you just found a key difference and I'm...so let's double test...let's double-check that we could still do it with two batteries as you propose in your method. And then we'll see if it has to be in a circle. ... 67 Teacher: Hm. Interesting. So, is this a circuit?		Defers to students' use of evidence to sanction ideas ("You wanna try it?"; "let's double-check that...") Makes benign comments ("interesting").
71 Teacher: Alright, let's try it with double battery. ... 77 Teacher: It's brighter. Interesting. So, you just discovered a key compon...a key thing about electricity.		Makes benign comments ("interesting"). Defers to students' use of evidence to sanction ideas ("Let's try it with a double battery.") Points out that students have discovered a "key thing."

In this episode, the teacher did very little to assist student sense-making and defers to laboratory evidence to sanction new knowledge. When students appeared to not be progressing, she quickly found a pedagogical tool and employed the pedagogical move of drawing students' attention differences in apparatus configurations. When they recognize the answer, she suggests that they test it, thus deferring to

students use of laboratory evidence to sanction new knowledge in the classroom. To summarize, the teacher consistently employed three pedagogical strategies to facilitate students in the inductive process:

1. Deferring to the available laboratory evidence to determine the validity of students' ideas and explanations by encouraging students to test their assertions.

Example: "Do you wanna try it?"

Evidence: Lines 37, 61, 63, 71.

2. Making benign comments that appear to affirm students' attempts to observe, infer, and explain without evaluating the students' ideas or explanations.

Example: "Interesting."

Evidence: Lines 31, 33, 35, 39, 67, 77.

3. Explicitly drawing students' attention to differences in apparatus configurations and associated observations with the intent of helping them develop accurate explanations.

Example: "What's the difference between those two set-ups that you made?"

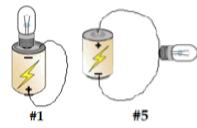
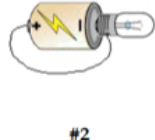
Evidence: Lines 31, 35, 49, 53.

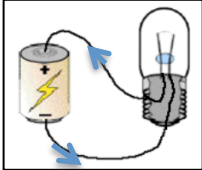
Analysis of Video 3, Part III - The Case for Scientific Induction

Above, I claim that *scientific induction*—the process of moving inferentially from the observation of concrete, specific instances of a phenomenon to an abstract, generally applicable principle—occurred. Given the centrality of induction to the PET curriculum (and not coincidentally to scientific inquiry more broadly), a more detailed analysis of the transcript evidence focusing solely on the evolution of students’ ideas toward and resulting in induction of a general principle is warranted.

As with the analysis of teacher moves, this analysis is condensed into table format. The condensed analysis is provided below in Table 6.5. This condensed analysis provides transcript excerpts in the left column, graphical aids to help the reader understand the subject matter context in the middle, and inferences about students’ ideas in the right column. Note that the first part of Table 6.5 is the Initial Ideas activity, as labeled, and that the second part is the Collecting and Interpreting Evidence activity. These data show the evolution of students’ ideas toward the induction of an abstract, general scientific principle: *all components of an electrical system must form a complete loop for electricity to flow*. The unit of this analysis is the laboratory group consisting of Dion, Tina, Manuel, and Sonia (Tina is absent for the Collecting and Interpreting Evidence activity). The full analysis is provided in Appendix D.

Table 6.5. Students' evolution toward general circuit principle.

Initial Ideas		
Transcript Excerpts		Inferred Students’ Ideas
14 Sonia: Because um, we need the positive and the negative um charge to make something work. So, if you want to make the light bulb light you would have to make it touch the wire because that's where the negative and positive come together.		Something leaves the positive and negative ends of an energy source and meet at the bulb to produce light. (The “clashing currents” model: configuration 1 will not work, but configuration 5 will.)
32 Sonia: Because um...the wire has to touch the negative part. 33 Teacher: 'Cause the wire has to touch what? 34 Sonia: Um, the negative side of the battery. 35 Teacher: Oh, interesting. Oh, you're saying because the wire is not touching the battery. 36 Sonia: It doesn't make the circuit work.		The wire must make contact with the positive and negative sides of the battery. Does not yet recognize the electrical path through the bulb.

Collecting and Interpreting Evidence		
Transcript Excerpts		Inferred Students' Ideas
32 Manuel: Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know? And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that. 34 Manuel: And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up. [Other students are toggling the overhead lights, presumably so that they can see if their bulbs are lit.]		A light bulb must be directly connected at each end to the electrical system (with one wire touching the side and one touching the bottom).
The students make several changes trying to get the bulb that is connected to the (+) of one battery and the (-) of another to light, including swapping the polarity and removing the bulb from the holder. 29 Teacher: Is that what you expected? [to Sonia] 30 Sonia: I was expecting it to light. Um, not gonna work.		The positive end of a battery and the negative end of a battery, though not necessarily the same battery, must be connected to the bulb for it to light.
56 Sonia: "It's not getting the whole circuit." 57 Teacher: "What do you mean when you say circuit?" 58 Sonia: "It's supposed to make like, like it's a circle of life. " [traces a circle on the paper with her finger] 59 Teacher: "Oh, interesting. That's interesting. 60 Sonia: "That's how you're supposed to...There supposed to connect each other and, like, either these have to be touching like that [puts batteries in series (stacked end to end)] and then one wire would have to come from here and the other one from here (the top of the top battery) and then connect to this (the bottom of the bottom battery) and that would probably..."		The positive end of a battery and the negative end of a battery must be connected to each end of a bulb for it to light. The components of an electrical circuit must be directly connected on each end, thus forming a complete loop, for electricity to flow. <i>Note: These last two categories are distinct in that one specifically pertains to a battery, the other to all components. A distinction between these categories is not resolvable in these data.</i>

The phases of student understanding and supporting evidence summarized in Table 6.5 provide insight into how these students' thinking evolved as they engaged the curriculum. Beginning with common student ideas about electrical circuits, the curriculum was carefully designed to guide students in collecting laboratory evidence and reconciling their current conceptions with that evidence. This group of students was led by the curriculum, with careful guidance of the teacher, to infer the target idea. Figure 6.21

suggests phases of understanding and a probable sequencing that, based on these video data, these students experienced. Students often begin with common alternative conceptions, such as the “clashing currents” model. Students then infer, separately, that the bulb must be connected at the bottom and side and that the positive and negative ends of the same battery must be connected into the circuit, as shown in Section B of Figure 6.21. Students then may infer that each component of an electrical circuit must be connected into the circuit at both ends, which is physically the same as the idea that they must form a loop, for electricity to flow (shown in Section C). Finally, some number of instances of this phenomenon may be observed before students infer that this circuit principle is generally applicable, as shown in Section D of Figure 6.21.

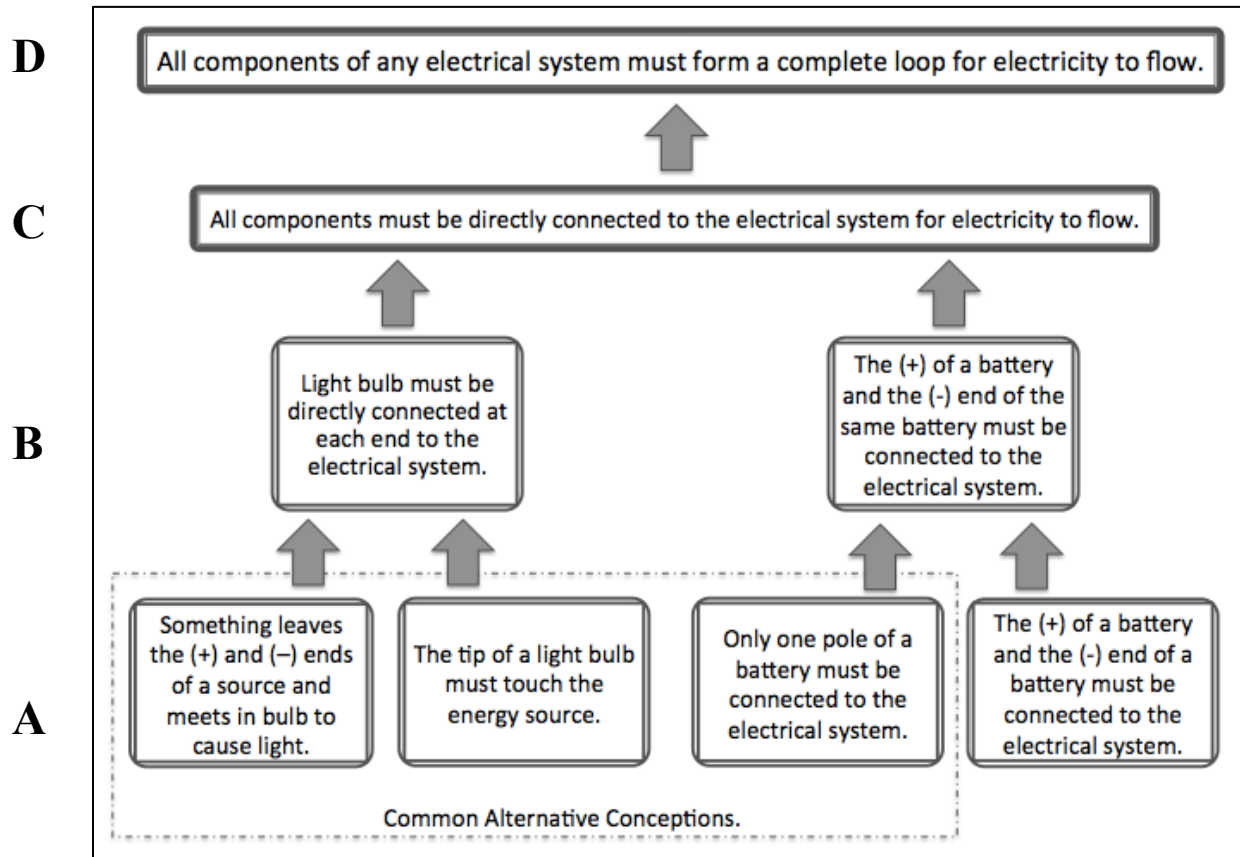


Figure 6.21. Evolving conceptions toward general circuit principle.

The sequence in Figure 6.21 certainly does not represent the only way that a learner may arrive at this general principle. Rather, it is a plausible sequence that is consistent with the design of the curriculum and the video evidence analyzed here. One may argue that the process of scientific induction is not complete until the explanation has undergone the consensus-building process. In the PET classroom setting, this would mean that the class would need to reach consensus on the best explanation for the evidence available. I will not argue for one position or the other here. However, the consensus-building activity, the Summarizing Discussion, will be analyzed in the next section.

Summarizing Discussions

The final principle activity in the PET learning cycle is the Summarizing Discussion. Students have shared their initial ideas, collected and interpreted laboratory evidence, and are now ready to come to consensus on the target ideas of this set of activities. This process begins by engaging the Summarizing Questions provided in the curriculum. The role of the summarizing questions as a pedagogical tool for scaffolding students in the process of scientific induction cannot be overstated. These questions are essential to the making of inferences by students to arrive at the general principles that are the target ideas of the curriculum. Students answer these questions individually and then work in their lab groups to come to consensus on the answers that will be presented to the whole class. The class then forms a circle, as shown in Figure 6.22. Answers are then presented to the whole class by each group using a large whiteboard, and a discussion takes place in which the best explanations that account for all of the available evidence are arrived at through consensus building. The whiteboards are an essential tool for both the group work of generating and presenting answers to Summarizing Questions and for the teacher to assess the developing ideas of the students.



Figure 6.22. Summarizing Discussion.

This Summarizing Discussion occurred after the completion of *Experiment 2: How do the two*

ends of the battery need to be connected to the two sides of the bulb? The students addressed the following

Summarizing Questions:

Summarizing Questions:

1. Draw a diagram of a battery, a bulb, and wire configuration that will light the bulb.
2. Draw a diagram of a battery, a bulb, and wire configuration that will NOT light the bulb.
3. What did you observe when you connected the configuration shown here? Explain these results.

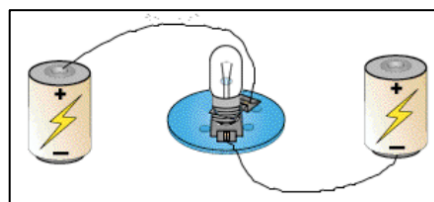


Figure 6.23. Chapter 5, Activity 1 Summarizing Questions.

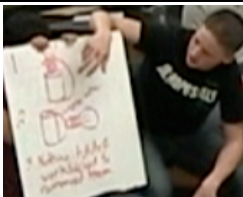
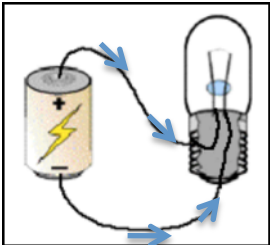
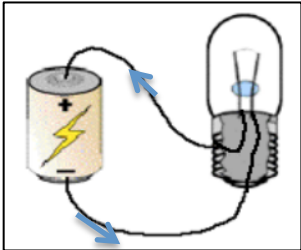
Examination of Chapter 5, Activity 1 Summarizing Questions in Appendix E reveals that the teacher chose to engage these students in versions of the summarizing questions earlier than prescribed in the curriculum. This is an example of one of the many pedagogical decisions that this teacher made when adapting this undergraduate curriculum for the high school setting. In this case, these questions were given early to organize the achievement of target ideas into smaller chunks and ensure students the opportunity to make sense of key phenomena before moving on.

Analysis of Video 4 – How do students engage in the task of seeking consensus in this Electrical Circuit Interactions Summarizing Discussion? How does the teacher facilitate student consensus building in this Electrical Circuit Interactions Summarizing Discussion?

A condensed analysis of this Summarizing Discussion is presented below in Table 6.6. The right column presents transcript excerpts, the middle column presents teacher moves, and the third column presents inferences made about students' ideas.

Table 6.6. Summary of teacher moves and student ideas in Summarizing Discussion I.

Transcript Excerpts	Teacher Moves	Students' Ideas
15 Sonia: So, in the arrangement of number one, it actually lit up because there was a full circuit meaning that the negative, the positive went to the light bulb and back. So, it just goes around in a circle. And also the light bulb was being touched in the side and in the bottom, how we said it needed to touch in order for it to light. 		The bulb must be connected on the bottom to one pole of the battery and on the side to the other pole. The components must form a complete loop.
18 Teacher: Thank you for sharing. Nice job getting it started. Thank you, Sonia.	Teacher makes benign comments. ("thank you for sharing"). Does not evaluate students' ideas.	
19 Julio: Um, for the first one we did the same thing as that group over there, except ours was different because we just wrapped our wire around the top of the bulb. And then the negative side was touching to the tip of the bottom part of the light bulb. So it, um, lit up.		The bulb must be connected on the bottom to one pole of the battery and on the side to the other pole.
22 Teacher: Thank you for sharing your first two. Very nice.	Teacher makes benign comments. ("thank you for sharing"). Does not evaluate students' ideas.	
22 Any questions so far? How do we feel? Do we agree with the observations these groups saw? If you don't, if you've seen something difference in your observations, let's talk about it. Be sure to bring that up.	Teacher encourages sharing of contradictory ideas or observations.	
26 Marco: Um, the second one didn't light up 'cause it's not uh, it's not really a circuit. It's kind of just like [inaudible] yeah. 27 Teacher: What do you mean when you say it's not a circuit? 28 James: It doesn't make a loop [gestures index finger in a circle], it doesn't, it doesn't allow for feedback. 		The components must form a complete loop.
31 Teacher: Thank you. I want. Thank you for sharing. Um, nice explanation.	Teacher makes benign comments. ("thank you for sharing"). Compliments adherence to norms. Does not evaluate students' ideas.	

32 Chris: So, basically as you guys all found out, it didn't matter the path you did as long as you went from a positive to a negative connecting to different like points on the light bulb, it worked. Then for our second one we basically did the same one as everyone else. We just used one wire connecting both the positive and the negative through one point which obviously didn't work. 33 Teacher: And specifically, why doesn't number two work? 34 Chris: Because it wasn't able to create a full circuit. 35 Teacher: OK. 36 Chris: It was like collid--I though it was like clashing energies almost. Like it wasn't able to keep going through.	 	The bulb must be connected on the bottom to one pole of the battery and on the side to the other pole. The components must form a complete loop. Variation of “clashing currents” model.
Transcript Excerpts	Teacher Moves	Students' Ideas
39 Teacher: Interesting. OK. OK. So you would be touching two different parts of that bulb. 40 Chris: Yeah. 41 Teacher: Thank you very much for sharing.	Teacher makes benign comments. (“thank you for sharing”). Compliments adherence to norms. Does not evaluate students' ideas.	
31 Um, nice explanation. I want us to hold onto that as we go into question three. 47 Teacher: Very nice. So yeah that wouldn't work because it doesn't make that complete circle back. Very nice. Thank you! So, just in closure for questions one and two, what parts of the light bulb must the battery or the wires touch? 48 Julio: the tip and the side. 76 Teacher: It wasn't a complete circuit? 'Cause what? 77 Sonia: The energy wasn't going around. 78 Teacher: The energy wasn't going around. So, to be a circuit, what do we have to have? 79 James: Continuous flow. 80 Dion: Continuous energy. 81 Teacher: A continuous flow and [points at Dion] and you're saying continuous energy. Interesting. So, it has to be. I saw James go like this. 82 Sonia: It has to be a circle. 83 Teacher: It has to be a circle. Very nice. Go ahead. 97 Teacher: Interesting. Can I repeat what you just said? And tell me if I'm right...on what you said. So, you're saying energy is going around in a circle and you're saying there's positives and negatives going around.	Teacher emphasizes target ideas once consensus is apparent. 	

In this Summarizing Discussion, the students offered their answers, and the teacher consistently thanked and complimented the students for their efforts. Some of the students' answers were given with

thorough explanations and others were expressed simply using the words “circuit” or “complete circuit” with no accompanying explanation of the terms. The teacher probed these groups for further explanations, and the students complied. Once the majority of the answers were given, the teacher began to emphasize the target ideas of this activity, the correct connection of the bulb and the *circuit principle*. Just as in the Initial Ideas and Collecting and Interpreting Evidence activities, the teacher refrains from evaluating students’ ideas. One may argue that the heavy emphasis that the teacher placed on the *circuit principle* is, in fact, a tacit valuing of this idea. There is no question that this is the target idea that the teacher wants, and the curriculum is designed to, guide students to. However, it is clear from this transcript that the students offered answers consistent with this target idea and that the teacher probed the more ambiguous answers to verify this common understanding before she began to emphasize the target idea.

At the completion of this Summarizing Discussion (and every Summarizing Discussion in PET), the students are given a *Scientists’ Ideas* handout. The *Scientists’ Ideas* activities were designed to provide students the opportunity to compare their consensus ideas to those of the scientific community and to bring closure to the learning cycle. A sample *Scientists’ Ideas* sheet is provided in Appendix G.

In this episode, the lab groups largely arrived at consensus independent of the others. Because of this, there was no apparent reason for disagreement and argumentation. The teacher even encouraged the students to disagree with one another in line 22, but their observations appeared to lead them all to the same conclusions. As we will see next in the analysis of another Summarizing Discussion, there was not always such broad agreement by the end of each learning cycle.

Observation: *In this Summarizing Discussion, students participated as expected.*

Observation: *In this Summarizing Discussion, the teacher refrained from making evaluations of students’ ideas.*

Observation: *In this Summarizing Discussion, once the consensus ideas were apparent and agreed upon by the students, the teacher emphasized the target ideas.*

Analysis of Video 5 – How do students engage in the task of seeking consensus in this Light Interactions Summarizing Discussion? How does the teacher facilitate student consensus building in this Light Interactions Summarizing Discussion?

A second Summarizing Discussion was analyzed to determine how students engaged in and how the instructor facilitated this consensus-building discussion. This video was chosen to supplement the previous Summarizing Discussion, which showed clearly how the teacher facilitates such a discussion, but lacked disagreement among the students. Disagreements were not uncommon in the Summarizing Discussions and often arose from different interpretations of evidence that resulted in contradictory explanations or models. Although less common, there were at times disagreements over the actual observations in the laboratory, such as whether or not two light bulbs in a circuit were the same brightness.

Background

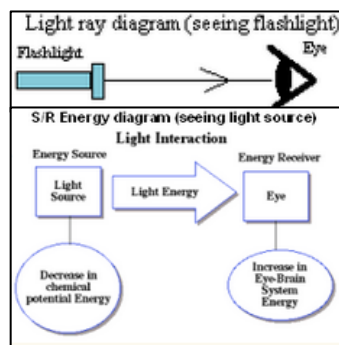
This discussion occurred in the final chapter of the PET curriculum, Light Interactions. The discussion is the culmination of Chapter 6 Activity 1. This activity is designed to address several target ideas, shown in Figure 6.24.

C6A1 Target Ideas:

A light interaction occurs when light illuminates an object. During a light interaction, **light energy** is transferred from a source to a receiver, there is a decrease in energy in the source, and there is an increase in energy in the receiver.

When you look at a light source, light interacts with (enters) your eye.

In terms of energy, when you see a light source, light energy is transferred from the flashlight to your eye. There is a decrease in chemical potential energy inside the source and an increase in the ‘eye-brain’ system energy inside your eye/brain.



C6A1 Target Ideas (continued)

When light interacts with a shiny object, the light is reflected in a particular direction. The angle at which the light reflects from the surface equals the angle at which the light strikes the surface.

When light interacts with a white, non-shiny object, the light is reflected in all directions away from its surface.

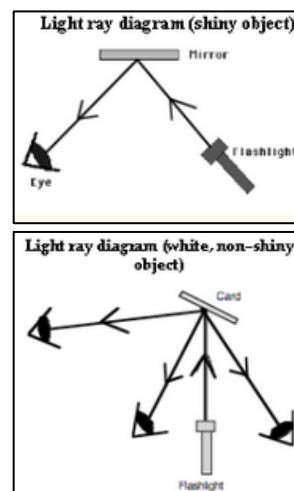


Figure 6.24. Chapter 6, Activity 1 Target Ideas

The design of this set of activities is informed by research into common student ideas about light (Goldberg, Otero, Robinson, 2010). For example, many students think that light reflects from a mirror in all directions and often do not recognize that the mirror only reflects light in one particular direction. Many students also initially think that when light shines on a sheet of white paper, the paper is just illuminated. They do not recognize that light reflects from the paper in all directions away from its surface and into the eyes, and that's how we see it. Finally, many students do not recognize that when one sees an object, light from the object enters the eye. This is particularly common in thinking about seeing a non-shiny object, like a piece of white paper. Students often think that they can see the light that illuminates the paper without the light ever entering their eyes. These activities are designed to address these ideas, and are guided by the central questions:

Guiding Questions:

- How does light interact with a shiny surface?
- When you look at a light source or a mirror image, does light interact with your eye?

Figure 6.25. Chapter 6, Activity 1 Guiding questions.

Students begin this chapter with the following Initial Ideas questions:

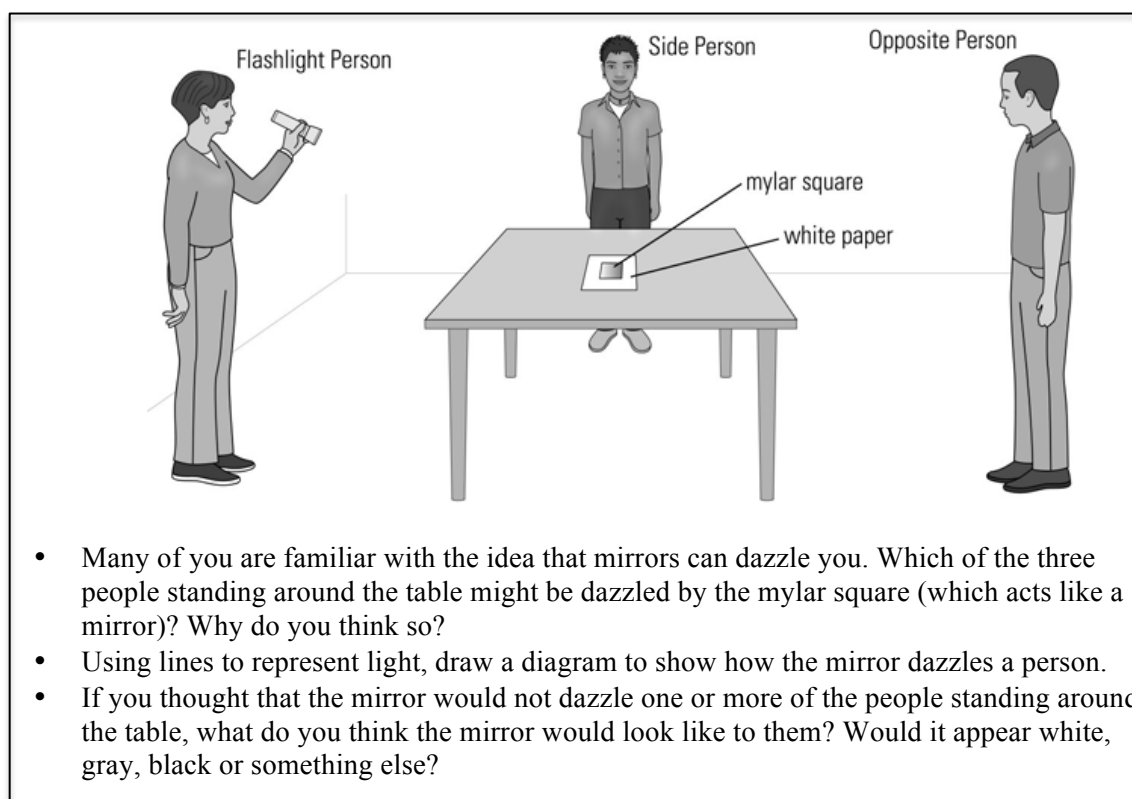


Figure 6.26. Chapter 6, Activity 1 Initial Ideas.

After sharing their initial ideas, students engaged a series of experiments which they investigated these phenomena, beginning with the *Experiment #1: What does each person see?* shown above in the Initial Ideas box. Next, in *Experiment #2: What happens when a beam of light strikes a shiny surface?* they shine a light on a white piece of paper as shown in Figure 6.27, followed by reflecting a light beam off of a mirror and onto the white sheet of paper as shown in Figure 6.28.

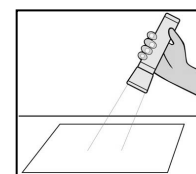


Figure 6.27. Exp. 1.

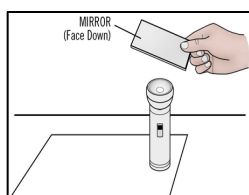


Figure 6.28. Exp. 2.

In these two experiments, the students are to observe that a light beam will be reflected in a particular direction when it is shined onto a shiny surface, such as a mirror or piece of mylar. The students also observe that light incident on a white, non-shiny

surface will be reflected in many directions.

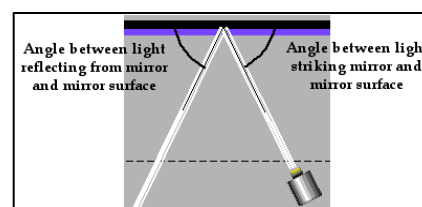


Figure 6.29. Exp. 2 Simulator.

Continuing Experiment #2, they investigate the relationship between the angle at which a light beam strikes a reflective surface and the angle at which it is reflected. Through a simulator activity, shown in Figure 6.29, the students determine that the angle of incidence is equal to the angle of reflection for a light beam striking a smooth, shiny surface.



Figure 6.30. Exp. 3.

Then, in *Experiment #3: When you look at a light source, or a mirror image of a source, does light interact with your eye?* students use a flashlight to investigate light

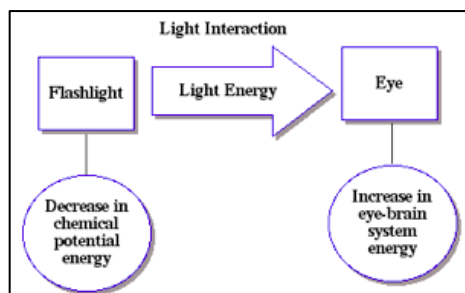


Figure 6.31. Energy diagram.

interacting with their eyes. Students observe each others' pupils contracting when the beam from a flashlight strikes their eyes, as shown in Figure 6.30. The students then engage in completing Source/Receiver Energy diagrams in which they account for light interactions using energy. An energy diagram for a single flashlight to eye interaction is completed, shown in Figure 6.31,

and an energy diagram for the more complex flashlight-mirror-eye interaction is completed as well, shown in Figure 6.32. After completing the energy diagrams, students are advised how to produce ray diagrams, such as the one shown in Figure 6.33.

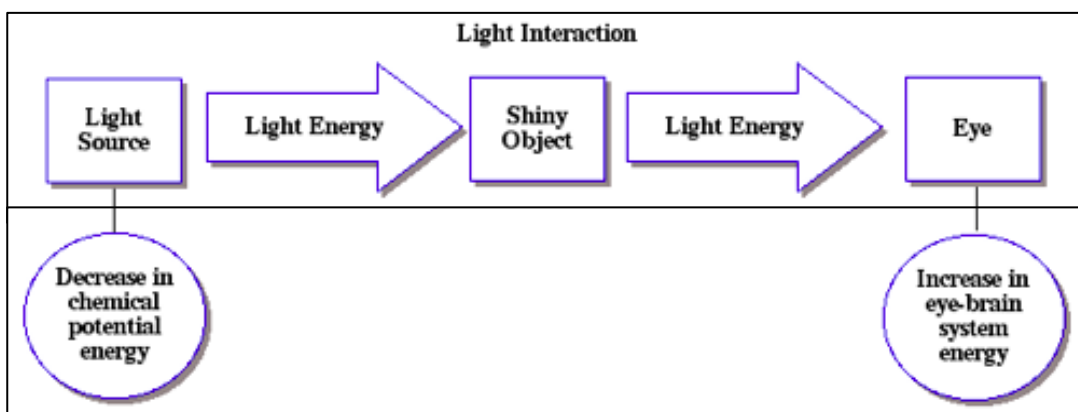


Figure 6.32. More complex energy diagram.

The diagram depicted on the right shows the path of a beam of light for the scenario pictured on the left. Note that there is no Observer B in the illustration on the left, though observer B is depicted in the diagram. These ray diagrams are intended to become a useful tool for students to answer the upcoming Summarizing Questions.

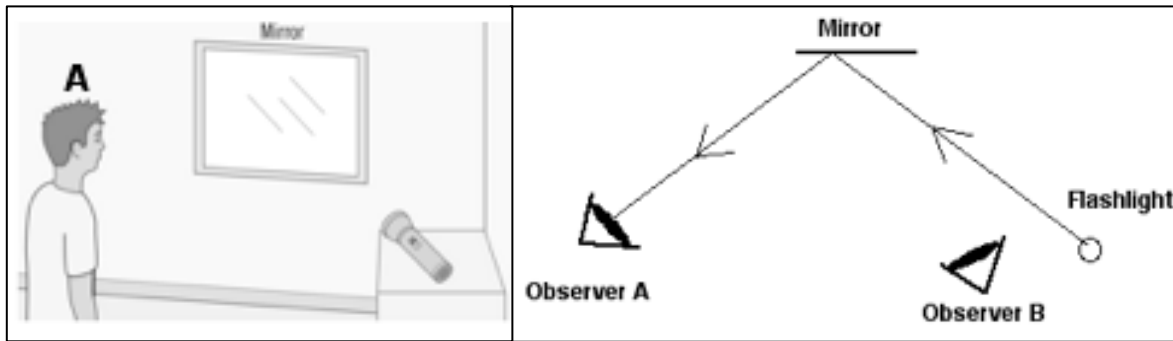


Figure 6.33. Ray diagram.

Once the three experiments in this activity are completed, the students engage the Summarizing Questions below in Figure 6.34.

Summarizing Questions:

1. How does light interact with a shiny surface? What evidence from the activity supports your answer?
2. When you look at a light source or a mirror image of a light source, does light interact with your eye? What evidence from the activity supports your answer?
3. Below is a side-view diagram showing a (light) source, a small mirror, and four observers looking toward the mirror. Which of the observers, if any, would see the reflection of the light source in the mirror. Support your answer by drawing a light ray diagram below.
(Note that the correct light ray is drawn in here).

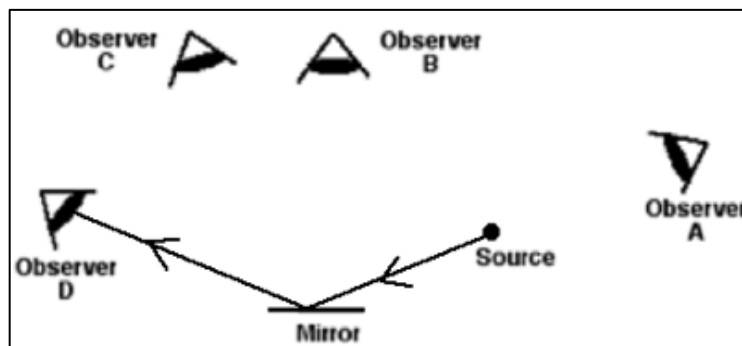


Figure 6.34. Chapter 6 Activity 1 Summarizing Questions.

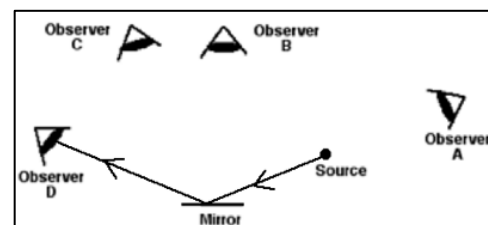
This Summarizing Discussion was facilitated by the researcher/author and was video recorded by the teacher. For brevity, this analysis focuses on a transcript excerpt in which a disagreement among the students becomes apparent and is eventually resolved and illustrates the moves that both the instructor and the students make to resolve the disagreement. The students are arranged in a circle with the researcher seated among them, as shown in Figure 6.35.



Figure 6.33. Summarizing discussion – Light

We enter the episode five and half minutes into the Summarizing Discussion with a student reading the third Summarizing Question.

- 1 **Doug:** OK, question 3. The question was. Wanna do that Tina? You've got the paper.
- 2 **Tina:** (Reading from her paper) Below is a side-view diagram showing a (light) source, a small mirror, and four observers looking towards the mirror. Which of the observers, if any, would see the reflection of the source in the mirror. Support your answer by drawing a light ray diagram above.
- 3 **Doug:** So, what'd you guys draw? (Looking at Chris)

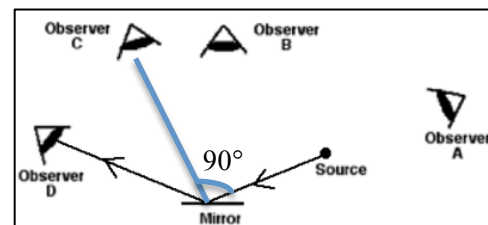


- 4 **Chris:** Well, I said "assuming the source did hit the mirror at the right angle D would be the only observer to see the light. That's what I said.
- 5 **Doug:** Anybody else got any different answers?
- 6 **John:** I said it would be the Observer C.
- 7 **Doug:** Aw, now we got a debate! Whoo!
- 8 **John:** It hit him right in the face but everybody else would see a little bit of light on the side.

Chris offers his group's answer to question #3 in line 4, stating that only Observer D would see the light. Doug asks for other answers, and John challenges Chris's assertion in line 6. John's group thinks that Observer C would see the light. Doug shows his excitement in line 7 that the students have something to argue about with an emphatic "Aw, now we got a debate? Whoo!" John further clarifies his group's position saying that "It hit him right in the face but everybody else would see a little bit of light on the side." It is not clear exactly which observer John means by "him." It is not possible to tell if he means observer C or D when he says "him."

Below, José joins the conversation and reminds John that the angle of incidence must equal the angle of reflection.

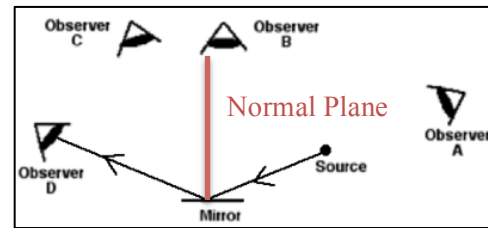
- 10 **José:** Remember, it's supposed to hit at the same angle. Why do you think it's C, John?
- 11 **John:** Because it's kinda how I drew it.
- 12 **Lydia:** But, if you draw a line from the light



- source to there, you would see that if you were trying to make it into a triangle observer C would sort of be at a right angle observer B would be um... (Shown at right)
- 13 **Doug:** Isosceles triangle
- 14 **Researcher:** OK, so there seems to be some disagreement arising from how you drew the actual incident and reflected rays (to John). Anyone else want to input into that?

Lydia also joins the debate, offering a geometrical explanation in line 12, stating that observer C is at a right angle relative to the path of the source and the mirror. Doug tries to help by naming a familiar geometric shape. The researcher notes the contradicting explanations and encourages others to input into the conversation. Kevin joins the conversation by asking if a person standing along the normal plane (perpendicular to the mirror, in this case Observer B) would see the light too.

- 15 **Kevin:** I got a question, um, like if you were
like standing like where the normal
(perpendicular) plane would be able to see the
light a little bit of light too or no?



- 16 **Researcher:** Standing where where? Where what?
- 17 **Kevin:** Like, let's say the source hit observer D and the normal (perpendicular) plane
would hit observer B. Would observer B see a little light too or no?
- 18 **Researcher:** Hmmm...
- 19 **John:** I think he would. He's on the side
- 20 **Researcher:** You think he would.
- 21 **John:** He's on the side.
- 22 **Laura:** I think he would because that's how our experiment did.
- 23 **Researcher:** That B would see something? The person along the (perpendicular plane)?
- 24 **John:** I think they all see a little bit of something.
- 25 **Researcher:** A little bit of something?
- 26 **John:** Yeah.

Kevin's question above asks if observer B would see anything. John joins immediately and sticks to his previous answer that the other observers would see the light in lines 19 and 24. Laura also sides with John in line 22, citing the observations that she made in her experiment.

Below, the researcher reminds the class of evidence that was brought to bear in an earlier question.

- 27 **Researcher:** Is that...does that concur with the evidence that Lydia brought from the experiment?
- 28 **Chris:** No.
- 29 **Researcher:** No? why not?
- 30 **Chris:** Because we said that um. Yeah, we said that the other person wouldn't see the reflection.

Chris responds above that John's and Laura's claims are incorrect, restating his answer without logical or evidentiary support. Below, it appears that the researcher believes that there may be some misinterpretation of the diagram and attempts to clear that up.

- 31 **Researcher:** OK. When we think about the experiment that we did where the mirror is flat on the table, where is the normal (perpendicular plane) if the mirror is flat on the table?
- 32 **Doug:** 90 degrees
- 33 **Researcher:** Ok. So, where would observer B be if the mirror were flat on the table?
- 34 **John:** He'd have to be above. (other inaudible responses)
- 35 **Researcher:** Ah, did we test that?
- 36 **Laura:** No.
- 37 **Sonia:** Actually, I stood on top of the chair and it hit me in the eyes and it hurt.
- 38 **Doug:** So, it does hit the normal (perpendicular plane)?
- 39 **Researcher:** That's the question we are...
- 40 **John:** Depends on the mirror.
- 41 **Researcher:** ...debating
- 42 **Doug:** Well, maybe we should do it real fast.

John responds that observer B would be above the mirror, and the researcher asks if that was tested in the experiment. In line 36, Laura says "no," indicating that her group may have misinterpreted the design of the experiment. Sonia, however, says that her group did do that, and it hurt her eyes. It remains unclear

what led her to this conclusion. In line 40, John says that it depends on the mirror, and Doug suggests that they retest it.

Below, Sonia warns Doug against doing the experiment again, presumably because she believes it will hurt his eyes. The group performs the experiment again as shown in Figure 6.36.

43 **Sonia:** Don't do it

44 **Researcher:** OK. [Gets up and grabs a flashlight and a mirror.] So, why don't we put it on the floor, and we can have someone be normal (perpendicular). Who wants to be normal?

45 **Doug:** I'm normal.

46 **Researcher:** OK. And why don't we have someone over here [Observer at angle equal to incident light (Observer D in SQ)]?
[Lights go out]

47 **Doug:** Nope. (singing) Ain't no sunshine when she's gone. [Lots of laughter; lights come on]. So, B will not observe it. So, that guy is x'ed out.



Figure 6.36. Redoing the experiment.

Doug, the observer along the normal offers his observation that he did not see any light musically, eliciting laughter from the class. The experiment confirms that only observer D will see the light beam.

The episode above clearly shows disagreement among the groups as to which observers will see a light beam incident on a mirror. Though several students weighed in, bringing observations and established physical relationships to bear, these did not resolve the argument. It is unclear how so many students recalled observing different things, though it may have been misinterpretation of the diagram in the Summarizing Question. Whatever the reason, one student, Doug, suggested that they resolve it by simply retesting it. Fortunately, this is a very simple experimental setup, and the materials were at hand to

easily retest this, resolving the dispute. After the Summarizing Discussion, students were given the *Scientists' Ideas* handout in order to compare their consensus ideas with those of the scientific community.

The researcher facilitating this discussion, like the teacher in all other analyses presented here, deferred to the evidence available to resolve this disagreement. Likewise, when Doug saw that the argument was not being resolved he suggested they retest it. There were two physics experts in the room, myself and the teacher, yet the students did not ask us for the “right” answer. They suggested that they redo the experiment and let the evidence resolve it.

Observation: *In this Summarizing Discussion, the teacher refrained from making evaluations of students' ideas and deferred to evidence to resolve a disagreement.*

Observation: *In this Summarizing Discussion, the students did not look to the two physics experts in the room to resolve a disagreement. They used laboratory evidence to resolve it themselves.*

Observation: *In this Summarizing Discussion, the students owned the process. They led the Summarizing Discussion and dictated the course of the activity by deviating from the standard script of the activity to redo the experiment.*

Summary of Findings

The observations made in each segment of video analysis are compiled below in Table 6.7. Each observation made in the preceding text is listed along with the video segment that it was derived from. Some of the observations, such as “students shared a range of ideas of varying degrees of scientific accuracy” from Videos 1 and 2 were made only in the Initial Ideas videos. This is because the expectations associated with the Initial Ideas activities result in each group, and thus all students, sharing their ideas. Other activities, such as Collecting and Interpreting Evidence do not provide opportunities to collect data in which large numbers of students share a range of ideas (unless a video camera filmed each group, a situation that was untenable given the resources of the project). Note however, that one observation, that the teacher refrained from making evaluative statements about students' ideas appears in every video

analysis. These observations are bolded in Table 6.7 below, and represent a finding that occurred across all of the video data analyzed.

Table 6.7. Compilation of observations from video analysis.

Video	Observations from Interpretive Analysis
Video 1 Initial Ideas Ch.2	In this Initial Ideas activity, the students share a range of ideas of varying degrees of scientific accuracy. Though most students use formal language, such as “force,” some use informal language when sharing their ideas.
	In this Initial Ideas activity, the teacher refrains from making any evaluative statements about students’ ideas , including allowing everyday language to operate in the classroom
Video 2 Initial Ideas Ch. 5	In this Initial Ideas activity, the students share a range of ideas of varying degrees of scientific accuracy.
	In this Initial Ideas activity, the teacher refrains from making any evaluative statements about students’ ideas.
Video 3	Manuel is intensely interested and engaged in this task, so much so that he has an intense emotional reaction when the laboratory evidence does not align with his current conceptual model. And though he experiences frustration, curses, and disengages from the task momentarily, he returns to it and persists.
	These students were guided by curriculum and teacher through the processes of scientific induction.
	The students appear to enjoy engaging in scientific induction. When they realize that they have developed a key scientific finding, they take great pleasure in it.
	The teacher consistently employed three pedagogical strategies to facilitate students in the inductive process (including refraining from evaluation).
Video 4	In this Summarizing Discussion, the teacher refrained from making evaluations of students’ ideas.
	In this Summarizing Discussion, once the consensus ideas were apparent and agreed upon by the students, the teacher emphasized the target ideas.
Video 5	In this Summarizing Discussion, the teacher refrained from making evaluations of students’ ideas and deferred to evidence to resolve a disagreement.
	In this Summarizing Discussion, the students did not look to the two physics experts in the room to resolve a disagreement. They used laboratory evidence to resolve it themselves.
	In this Summarizing Discussion, the students owned the process. They led the Summarizing Discussion and dictated the course of the activity by deviating from the standard script of the activity to redo the experiment.

Analyses of these video data reveal five key findings:

1. **These students were guided by the curriculum and the teacher through the process of scientific induction.** This evidence-based, inductive reasoning entailed making many specific, concrete observations of physical phenomena and then moving inferentially to the development of a general, abstract scientific principle. These students’ participation in the inductive process is marked by persistence, emotional expressions of frustration and enjoyment, and what appears to be a commitment to understanding the phenomenon they are tasked with investigating. They persist through a series of

frustrating struggles to make sense of the physics and even argue about who will handle and tinker with the equipment to perform the task at hand.

2. These students appear to enjoy engaging in scientific induction. This enjoyment is evidenced by smiles, gestures of accomplishment and congratulations, and compliments for one another about completing the task.

3. The teacher employed three pedagogical strategies to facilitate students' scientific induction: (1) deferring to laboratory evidence to sanction students' ideas and explanations by avoiding the traditional school practice of evaluating students' ideas and encouraging students to test them for themselves; (2) affirming student effort and sense-making with both benign comments, such as "interesting" and compliments that appeared to value students' efforts, as opposed to openly valuing students' correct ideas; and (3) employing "on the fly" pedagogical strategies and tools, such as drawing student's attention to differences between the different possible configurations of the lab apparatus and the associated concrete observations they were making.

4. The students took ownership of the process of one Summarizing Discussion. They led one Summarizing Discussion and dictated the course of the activity by deviating from the standard script of the activity to redo the light experiment.

5. Student engagement in these tasks is marked by unequal participation. Within the lab group analyzed in this chapter, two of the four students handle the lab equipment exclusively and interact with each other and the teacher much more than the other two students.

CHAPTER7

CONCLUSIONS AND IMPLICATIONS

This examination of the implementation of the PET curriculum in the high school setting has yielded several findings with both practical and theoretical implications. Though this curriculum has been studied extensively as an undergraduate course (Goldberg, Otero, & Robinson, 2010; Otero & Gray, 2008, etc.), very little research about implementation in a high school setting has found its way into the literature (Belleau & Otero, 2012; Ross & Otero, 2012), and even fewer have focused on the effectiveness of this curriculum and its impact on student affect as a means to broaden access to science for groups that are historically underserved by, and therefore underrepresented in, the science and science education enterprises in the U.S.

To summarize, analysis of interview data resulted in the following findings:

1. Students became comfortable expressing their physics ideas and came to value having their ideas challenged and challenging the ideas of others.
2. Students expressed an awareness of the role that their own ideas play in the learning process.
3. Students came to value engaging in scientific practices, such as supporting claims with evidence, requiring evidence for others' claims, and constructing explanations through consensus.
4. Students perceived the teacher's role and power structure in this course to be different than in traditional classes and that this aspect had impacted the nature of their participation.

In short, these students perceived this experience to be markedly different from their other science classes and felt it to be both a comfortable, safe environment and an empowering experience. This contrasted sharply with the way that their statements depicted their other science and general schooling experiences. The data show that students' experiences in previous courses were marked with fear of saying what they thought, being made to feel stupid if they were "wrong," and being apprehensive about performing adequately. In contrast, their feelings of comfort and openness in the PET class were accompanied by a valuing of scientific practices and types of participation that were novel to them. These findings are

consistent with those of studies by Ames (1992) that found that prominent, normative evaluation resulted in a failure-avoidance mode in learning. This contrasts with a mastery orientation that was encouraged when evaluation was much less salient in the classroom.

The video data also yielded findings about how students engaged the PET curriculum activities and how the teacher facilitated these activities:

1. These students were guided by the curriculum and the teacher through the process of scientific induction.
2. These students appear to enjoy engaging in scientific induction.
3. The teacher employed three pedagogical strategies to facilitate students' scientific induction: (1) affirming student effort and sense-making with both benign comments, such as "interesting," and compliments that appeared to value students' efforts, as opposed to valuing students' correct ideas; (2) employing "on the fly" pedagogical strategies and tools, such as drawing student's attention to differences between the different possible configurations of the lab apparatus and the associated concrete observations they were making; and (3) deferring to laboratory evidence to sanction students' ideas and explanations by avoiding the traditional school practice of evaluating students' ideas and encouraging students to test them for themselves.
4. The students took ownership of the process of Summarizing Discussions.
5. Student engagement in these tasks is marked by unequal participation.

Given the assertion that scientific induction is the process that is central to scientific practice, indeed the process that distinguishes the sciences from all other disciplines, the video data presented show that these students have *experienced* science. Not only did they experience scientific induction, they enjoyed it. These students displayed intense engagement and persistence in making sense of laboratory evidence and eventually extracted a general physical principle from their data. This accomplishment was accompanied with affective displays such as smiles, compliments to one another, and hi-fives, strongly suggesting that scientific induction in the high school classroom is not only possible, it can be *an experience* for students. By *an experience*, I mean that students feel the power, control, and sense of

agency that effectively using the tools of science can afford. Through this experience, these data suggest that they came to realize that science is not a body of authoritative facts that they must obtain from a book, the internet, or a more knowledgeable other, as it is too often portrayed in our classrooms. Rather, it is a way of approaching the human experience that rejects assertions supported only by authority and takes a critical, evidence-based perspective that can transform the way one interacts with the natural and social worlds.

How do we explain such an experience? How did it come about? How did the enactment of this curriculum achieve results that traditional approaches, and most transformed models to date, too often fail to? As noted earlier, attempts to bring the experience of *doing science* to high school students has endured, and failed, for over a century. An examination of the curriculum and conversations with the authors has revealed that there is really nothing new or revolutionary in this curriculum. It is well-designed, based on rigorous research on students' ideas, and was laboriously developed and tested over many years, but none of the authors can claim to have done anything more than to model this course upon the learning of scientists.

Scientists engage questions and make concrete observations of the natural world in an attempt to move inferentially to some abstract, generally applicable principle (law), model, or theory. This curriculum was designed to model this process, referred to centuries ago as the *inductive method* (Bacon, 1878). As was stated earlier, not all scientific work is inductive, and most of the modern scientific work that occurs, such as the current search for the Higgs boson, is deductive. Kuhn (1977) referred to this deductive work as “normal science” and explains that this work fills in the details of the new and revolutionary theoretical framework that the scientific community has transitioned to. Of course, normal science is extremely important, but the scientific work that changes the world—that enacts paradigm shifts, or scientific revolutions—is brought about by the inductive method. Newton's Laws, the Universal Law of Gravitation, the Theory of Evolution, quantum theory, the laws of conservation of mass and energy, the 2nd law of thermodynamics, etc., were all developed inductively from observation and experimentation. This inductive method is the model of learning new things about the natural world that the PET curriculum was

modeled after. So, in a sense, it's the oldest pedagogy out there, excepting maybe lecture and the Socratic method. It predates the "inquiry" movement, project-based instruction, problem-based instruction, modeling, and high leverage practices, because it is simply the process by which science makes new knowledge and dramatically changes the way we describe and interact with the natural world. Yet, so little that finds its way into our classrooms brings this experience to students.

More studies are necessary to fully test the conjecture that engagement in scientific induction was a dominant factor resulting in positive reactions of the students in my study. However, using a critical perspective along with classic motivation theory allows for explanations of why this process might be more powerful than traditional models of science instruction. Taking a critical perspective to consider the power dynamics of the science classroom and science education more broadly can offer insight into why students in this study appeared to thrive in this learning environment. As stated above, science is often portrayed as a body of facts, passed down from an authority such as teacher or text, that students are required to "learn" without the means to understand how this knowledge is known or to experience for themselves the evidence from which this knowledge was developed. Furthermore, the social and cultural mismatch between those who write and administer the curriculum and those students from groups underrepresented in science may be a factor resulting in the small numbers of students being selected for academic success in science schooling. Regardless of the cause, these outcomes necessitate changes in the way that school science is conceptualized and enacted.

Considering the results of my study through the lens of classic motivation theory could lead to instructional designs that minimize evaluation as a mechanism for motivating students and provide opportunities for all students to engage in the development of their own ideas based on evidence that they collect. This study has demonstrated successful affective outcomes in various classroom inductive activities for students from groups underrepresented in science. The classroom environment in this study differed markedly from traditional environments. In this study, students' participated in knowledge-generating practices and consensus-sanctioning practices in which evidence and consensus replaced

traditional knowledge-conveying practices of authority. Evaluation as a mechanism for motivating students was replaced with participation and power as a mechanism for motivating students.

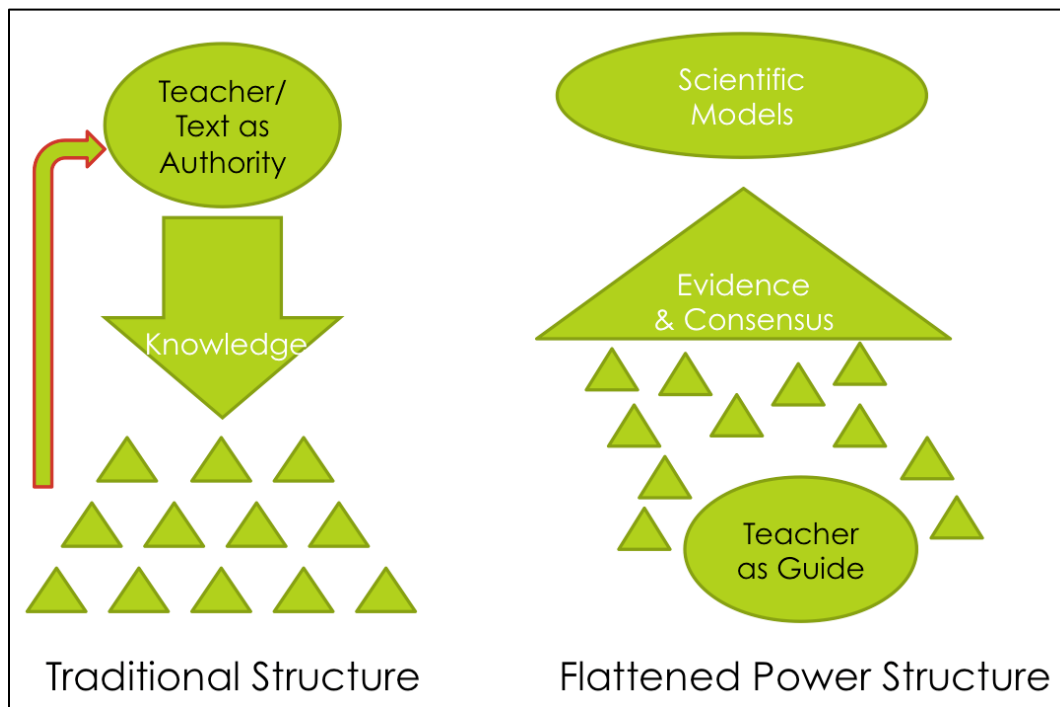


Figure 7.1. Explanatory model: traditional classroom dynamics contrasted with a flattened power structure.

This model of instruction is represented below in the left portion of Figure 7.1. In the traditional model, all ideas must either come from or be sanctioned by teacher and text. In a model of instruction that is based upon the epistemology of science (on the right in Figure 7.1), evidence and consensus are the only means of sanctioning ideas. The teacher's role in a classroom modeled upon science is to help students learn to use the tools of science.

Based on national data (Lee, 2001; NRC, 2007; NCES, 2011; NCES, 2009) and international comparisons (NCES, 2006), we can be reasonably certain that traditional methods are not serving our students well. We may infer that these methods render the students' natural curiosity, and their perhaps evolutionarily hard-wired drive to find order in and to make sense of the world, dormant or otherwise irrelevant to the tasks in which they are required to engage. This inference is supported by the findings of

Ames (1992) that suggest that traditional modes of school science and the evaluation and sorting that they entail can discourage the development of an appreciation for the intrinsic value of learning.

In scientific practice, the power to decide what makes sense, what the best explanation is given the evidence available, does not reside with some authority that is beyond reproach. Rather, it resides with anyone who will systematically collect evidence and make inferences from it that result in logically sound, evidence-based explanations that best account for what can be observed in the natural world. Throughout history, we have witnessed the challenging of the oppression of authority with the tools of science. From Galileo and Copernicus to Darwin and Einstein, many have challenged the dogma of the church, as well as the accepted theories of science at the time, to fundamentally change our understanding of the natural world.

The means by which such a transformation of our understanding of nature can be achieved—the inductive method—must be made available to our students. Thus, the fundamental reorganization of the learning environment from the misguided model of learning science by appealing to an authority to regarding evidence and consensus as the only means of sanctioning knowledge is long overdue. This fundamental transformation of the learning environment does two things. First, it accurately models science in the classroom, affording students the opportunity to understand what science is and does by doing it, by experiencing it. They may, like the students quoted below, take up the tools of science and come to value them.

Laura: *Like, what's your evidence? Your evidence then, like, "Well, I saw this"...like just telling them straight up, "Prove it. Prove that you know." ... I was like "Oh, how so?" you know like I just kept asking questions. Like we asked how – I know all of you guys like from the discussion circles and we are not gullible like we are not just going to believe something, because we want that evidence.*

Moises: *Not if they don't have any evidence, because then you don't know if they are lying...It depends on how they use their evidence.*

Second, this transformation positions students as those with the power and control over the development of their own understanding by engaging them in meaningful use of the tools of science toward the ends for which they are employed in actual scientific practice. Further, this engaged participation (Greeno, 1998) encourages students to take on identities as skeptics, critical consumers of the assertions of others, and those practiced in the use of the tools of science to support their own assertions and to challenge the assertions of others, as demonstrated by the students quoted below.

Laura: *And you wouldn't like to like argue with them because you would think they would take it wrong. So we just grew with each other and realized it was right to argue with each other because we were all doing it to help each other, not just to make you look bad in the circle and stuff.*

Laura: *Because there won't always be a person holding your hand telling you this is right. And Ms. Belleau pretty much does a great job of telling us you know you got to figure it out yourself. You got to stand on your own two feet and figure it out for yourself because you are not always going to have that person that's going to tell you "yes, you are correct" or "no, you are not."*

Sonia: *We used to be gullible before this class. We just took the information from the teacher and we were like, "OK, you're right, I guess."*

Maria: *So, like I think we've become, because we are expected to have evidence, I think we've become more of like in control of our education and like the choices we make so we kind of – and the information we are taking in and I think we've become more I guess open to the idea that we are in charge. So if we, you know, we need the information, we are going to ask for it. We are not going to sit around anymore and just have an OK explanation. We're not going to settle anymore, I guess.*

These students have taken on identities of skeptics, of those who understand that arguing can be a path to new understanding, and those who understand that they can and should take charge of their own learning. Is that not what we mean when we use the term "critical thinking?" Just like "inquiry" and "student centered," this term has become ambiguous, as it has been interpreted in so many different ways. I assert that critical thinking, and a critical disposition, can become meaningful and even useful if the experiences

we design for students can provide sustained and authentic opportunities for them to engage in the central practices of science. In this case, the shifting of the authority to sanction ideas from teacher and text to evidence and consensus has resulted in these students taking control of their own learning and suggests strongly that a transformation of how these students interact with the world has taken place.

Remarkably, one student's responses even explain a mechanism for this transformation.

Phoebe: *I feel like when classes like that, I feel like we're on like on equal ground. Like us and the teacher too. Like we know that she knows it more but she wants us to like be on her level if that's what she thinks ...*

It made me feel a lot more comfortable in that class. Like I felt a lot more comfortable asking questions like I didn't feel like she was going to be like "Oh, you're wrong."

...when she did that like it felt like we have the answers also, we just needed to discover them. Like it wasn't like you don't have the answers and I do. It's like we all have the answers.

This student appears to feel that the shifting of authority from teacher/text to evidence and consensus flattened the power structure of the classroom. It made this student feel that the students were “on equal ground” with the teacher and that they “have all have the answers.” She realized that in her other school experiences she was constantly judged by the teacher as right or wrong, and that in this course she could find the answers for herself.

I posit that the flattened power structure of this classroom allowed the teacher to take on an entirely different role, one that is a marked departure from the traditional modes of schooling. Rather than delivering information *about* science to students and then evaluating their renderings of it, she simply guided the students in the collecting of evidence to make inferences about nature. The authority to make sense of nature rested with the students. They became comfortable expressing their ideas and engaging in the central practices of science, because no person was judging them as they tried to make sense of their experiments. One of the principal findings of the second results chapter was that the teacher consistently deferred to evidence when the students posited ideas in the activities. In all of the observed activities in PET, the teacher refrained from rendering judgment on students' ideas, and when the students offered

explanations, she consistently asked them if they wanted to test them. The lack of authoritative evaluation appears to have allowed students to engage in ways that they appreciated, enjoyed, and that led to a greater sense of agency.

When science is experienced by students as an authoritative body of facts, to them it might just as well be religious or ideological dogma. When science is experienced by students as an approach to understanding the natural world in which they may effectively and successfully participate, they may come to perceive the scientific enterprise more accurately and perhaps stand a much better chance of positively identifying with these practices. The scientific approach is something to which we want to broaden access for a variety of good reasons (global economic competitiveness, maintaining democratic ideals, etc.). I have tried to argue that chief among these reasons is the idea that the process of scientific induction is inspiring, potentially leading humans to approach their own experience differently—from a position of skepticism, criticality, and the empowerment that comes with being able to support one's own claims. The very nature of science situates those who are scientifically literate in a position of control because they can discriminate between falsehoods and the relative value they place on claims. This could greatly impact and empower a student's approach to everyday life. Seen through a critical lens, the empowerment and sense of agency that might be achieved through scientific literacy may develop within students a disposition to question the "conventional wisdom" and the dominant narratives that rely on tradition rather than evidence of efficacy. Such narratives can and should be questioned, **both** by those of the privileged progressive establishment and also by those who are denied access and opportunity. It is only through the agency and skepticism of both that these systems of relations can be perturbed and perhaps even leveled to some degree.

Along with this sense of agency and skepticism may come an appreciation for the power and beauty of the inductive method. Just as the arts—literature, music, dance, sculpture, and paint—can evoke emotion, inspire, and transform, so too can the beauty and power of science. Just as sport, nature, craftwork, mathematics, and engineering can inspire and transform, so can experiencing the spirit of science. Witnessing and appreciating aesthetic beauty, such as the aurora borealis (northern lights), may be

inspiring, just as learning something about the products of science can be exciting. Yet, that is not *doing* science. Constructing an evidence-based model about how the aurora happens that has explanatory, and perhaps predictive, power *is* science. The spirit of science resides in the development of new understanding and defending that understanding with evidence, rather than in a familiarity with the products of science.

It is, perhaps the beauty and spirit of science that compels us, when we are tasked with teaching science to others, to try to convey all that has transformed us. We come under the false notion that we can deliver the abstracted principles to our students such that they may feel the spirit of science as well. Mann (1914) speaks of this tendency.

Current courses in elementary physics have been planned by students of advanced physics under the spell of a very one-sided appreciation of what the essential elements of physics are. For when a student under-takes to grapple with such works as Newton's "Principia," or Maxwell's "Electricity and Magnetism," he finds it no easy task merely to follow the argument and to reproduce the results. Hence he naturally acquires a great admiration for the intellectual genius of the men who created such works. He knows, moreover, that his academic success depends on his ability to reproduce these works as intellectual feats only. When he himself becomes a teacher of elementary physics, he very naturally falls into the habit of presenting physics as a series of intellectual feats—of facts and demonstrations and theories and nothing more. Hence current courses have been framed and many textbooks have been written with the sole purpose of teaching the laws and principles of elementary physics as coldly intellectual propositions (Mann, 1914, p. 516).

And thus it largely remains today that we present the abstract models, principles, and theories and ask naively for the students' faith in them. We then proceed to have them apply or regurgitate the abstractions that they struggle with and, more often than not, fail to understand. Of course, this failure is not a failure of or by the student, but a failure of the design and execution of science schooling. The results presented in this study strongly suggest that a redesigning and fundamental restructuring of school science to model actual scientific practice can provide the context through which students may develop these powerful and beautiful abstractions for themselves. Through this, they may not only understand and be able to apply the

products of science, but they may come to be able to engage in the discourse and practices of science. They may become *scientifically literate*.

One might argue, as some of my colleagues and mentors have, that the primacy of the scientific approach, that buying into that set of practices, is akin to falling prey to dogmatic assertions as well. That valuing the inductive method is no less a folly than blindly following religious or ideological dogma. To them I say, “Got something better?” In other words, is there a more objective, effective, and egalitarian approach to understanding the world? One that has produced more dramatic changes in the way we live, our quality of life, and even how we view the probability and means of our survival as a species? Not that I am aware of. Science in the ideal is empowering and egalitarian, because the authority resides with evidence that can be gleaned from nature rather than religious or ideological doctrine. Of course, as I have stated earlier, science in practice has historically fallen short of these ideals. It has a history of elitism, sexism, racism, and surely cannot be said to have brought only good to the human experience. Nevertheless, the epistemology of science is inherently egalitarian in that nature does not reveal her order differentially to those of different, race, age, gender, sexual-orientation, or class.

This study provides evidence of students from groups historically underserved and therefore underrepresented in science engaging productively in and enjoying the central practices of science. As we consider the phenomenon of cultural positioning and the large and obstinate disparities in science achievement and participation among racial and ethnic groups, the results of this study appear to question the conventional wisdom that *science itself* is responsible for the differential outcomes we cannot seem to resolve. These results indicate that “doing school” and the constant and damaging evaluation and sorting of students it entails are the problem, not science. Just as I have shown that traditional science schooling engages students in very little that resembles scientific practice, these results suggest that modeling school science after the pedagogy of scientific practice may be the great leveler science education has searched in vain for.

Of course, this study is small, confined to one setting, and thus the generalizability of the findings is quite limited. This curricular implementation, as all are, was also far from ideal, as one of the findings

from the video data show that there were obvious disparities in participation among members of the lab group. As noted in the first Results chapter, not all students made statements supporting each of the four findings in interviews. Likewise, many students were not interviewed at all, and their experiences remain largely unaccounted for. I am reasonably sure that other disparities in participation would be found in other groups and in whole class discussions, and as my work in this area continues I intend to address these disparities. Furthermore, the current context of schooling in the U.S. requires teachers to evaluate and grade, thus it should be noted that although this enactment of PET was a marked departure from traditional approaches, students likely still bore the effects, good and bad, of units tests and final exams. Yet, the evaluative aspects of traditional schooling were largely absent from the learning environment, and though tests were given and graded at the end of each chapter, the evaluative component was generally absent from the formative, sense-making activities analyzed in this study.

Given these limitations, the reason I chose to study this curriculum was because I saw such remarkable levels of engagement and discourse in the PET classroom. In my experience, this exceeded what I would expect for any high school class, especially a physics class that serves the entire student population at an underserved high school. It is not my intention to glorify this curriculum or its authors, one of whom is my advisor. Rather, it is my intention to report and make inferences about what the students shared with me and what I observed, and my findings suggest that the inductive method has great potential to change interest and performance in high school physics learning. Curricula developed with pedagogical and scientific expertise that provides the structure to enact scientific induction can be one means by which we transform school science. Viewed as such, a critical science curriculum is not a tool with which to teach science, it is a set of tools—a meta-tool—through which to engage students in the practices of science. The findings here suggest that this approach may hold great potential, and here I have presented empirical and theoretical reasons to support this assertion and further pursue the agenda of modeling the pedagogy of the science classroom upon the epistemology of science.

Implications for Science Teacher Education

The findings of this study suggest that current approaches to teacher education might be informed by the findings about students' experiences using a curriculum designed upon the inductive method. Not only do the vast majority of high school and undergraduate physics curricula completely disregard scientific induction, it is clear that the enactment of these curricula results in classroom practices that tend to misrepresent science. Furthermore, we have no reason to believe that the current science teacher preparation programs provide opportunities for our teachers to understand and engage in the central practices of science. The results of numerous studies suggest that they do not (Ross et al., 2011; Wallace & Kang, 2004; Windschitl, 2004). Teacher preparation programs may consider providing their students with experiences that help them understand, participate in, and reflect upon the central practices of science. Should we have any expectation that teachers who have never experienced the central practices of science for themselves can design and execute such experiences for their students? It may be that anything short of experiences of the inductive method will fare no better than the current modes of teaching students about scientific "facts."

Practicing teachers, who have very little time and resources to engage in sustained, formal learning, may learn what scientific induction is and come to value it by teaching with a curriculum designed to support their own practice-based experimentation with these methods. Though not a focus of this study, the teacher of record has consistently spoke of how using PET has completely changed her philosophy of and approach to science teaching.

Implications for Science Teacher Educators

With respect to research in science education, teacher educators interested in broadening access to science may wish to consider exactly what they intend to broaden access to. Improving access to the use of the products of science for social action may encourage familiarity with scientific principles and promote student agency, but it is difficult to understand why research on science for social or political action appears to completely avoid the central practices of science. It may very well be that such an approach

perpetuates and reinforces the misrepresentation of science as an authoritative body of facts, yet that is an empirical question.

The findings of this study suggest that the experiencing the inductive method promotes a disposition of skepticism and a sense of agency among students. This transformation involved developing an understanding that science knowledge is not authority-based, and that anyone can wield the tools of science to challenge or defend claims. That is the spirit of science, and no knowledge of scientific principles, however complete, can ever supplant its transformative power. Thus, science teacher educators may consider what it means to convey the spirit of science, to arouse and inspire our future science teachers, through the sharing of the inductive experience.

Implications for Physicists

Undergraduate experiences in physics can be difficult at best and are more commonly wrought with fear of failure. To what end does an attitude of elitism and the perception that physics is exclusive to a select few lead us? It may very well be that undergraduate physics instruction selects for success students that display qualities that have little to do with their potential to succeed as physics researchers or educators. We can be sure, based on the findings of this study and supported by those of Ames (1992), that instructional modes that encourage a normative sense of achievement can result in failure-avoidance, a mode that is perhaps the antithesis of the type of engagement that marks authentic scientific inquiry.

Physicists and physics education researchers may wish to consider how their recent course transformations to achieve more interactive modes of instruction may include opportunities for scientific induction. Laboratory experiences in particular may be a productive context in which to experiment with inductive approaches. Many laboratory experiences of undergraduate physics replicate the experiments that resulted in the paradigm shifts that reshaped our understanding of the natural world. Unfortunately, these experiences are often perceived by the student as tedious confirmatory exercises in measurement and calculation, rather than an experience of generating for oneself the general principles that govern nature. To be sure, the more advanced and abstract the physics subject matter, the more difficult it is to craft

relevant inductive experiences for students. Furthermore, it is not my intention to minimize the importance of engaging future physicists in laboratory work that requires tenacious persistence, perseverance, and attention to detail. However, just as the authors of PET carefully chose subject matter amenable to the inductive process, undergraduate courses for scientists may find this approach fruitful.

In effect, we are currently facing a dilemma in which the three sectors of science teacher preparation—teacher preparation programs, undergraduate science courses, and K-12 schools—are functioning in virtual isolation of one another to perpetuate the status quo of denying all students access to central practices of science. It may very well be that efforts to reform any of the three may be foreclosed if all three are not engaged in meaningful cultural and institutional change. I suggest beginning the addition of scientific induction to science teacher preparation by creating points of articulation between these three sectors. Scientists know how to conduct scientific induction, yet they likely have not enacted this process in their undergraduate courses. Teacher educators are perhaps best positioned to inform these reforms with their understanding of educational psychology, cognitive science, and cultural and institutional change. Finally, currently practicing K-12 teachers are the only experts that truly understand the challenges and strengths of the school and community contexts that they and their students operate within. These sectors must be bridged, and the walls that separate these communities torn down, if we hope to break the cycle of reproduction of learning *about* science rather than experiencing it.

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APPENDIX A: C2A1 Initial Ideas Full Transcript

- 1 **Teacher:** So, today we're gonna talk about questions three and five. Question three actually ‘
relates to question one, so can somebody...can I have one person volunteer to read the little
scenario that we're talking about before the questions?
- 2 **Denise:** Wait, on this page [points to sheet]?
- 3 **Teacher:** This one [points to question]. [Diana raises her hand] Alright, you guys quiet down
while Diana reads it.
- 4 **Denise:** Think about a soccer player and a stationary ball. As he interacts with it by kicking it, the
ball starts to move. After the kicked ball rolls across the grass it gradually comes to a halt.
- 5 **Teacher:** So, a soccer player is kicking a stationary ball. What does stationary mean?
- 6 **Many students:** Not moving.
- 7 **Teacher:** OK, so there's a soccer ball. The soccer player comes up and kicks that ball that's not
moving, causing it to roll along the grass and slowly come to a stop. Alright, so in question one,
you drew a graph. For question three, you showed where...I'm sorry, you showed where the forces
were acting on the ball. And then question five--will somebody read question five?
- 8 **Doug:** Now draw two pictures of the ball and each of them show the forces [inaudible].
- 9 **Teacher:** So, we have some pictures of the soccer ball and we use arrows to show the forces that
are interacting on the ball. So, um, starting with group six, will you guys stand up and share your
question...reading question five? [One lab group stands to present]
- 10 **Denise:** For question three it says 'Using a different colored pen, label where forces are acting on
the ball to push the ball forward. Explain your reasoning.' Well, we didn't have different colored
pencils, so what we did was underneath it [inaudible] we drew a line going up...or increasing
because when the forces were acting on the ball the ball had forces that moved, so it was
increasing instead of decreasing.
- 11 **Teacher:** So, is that the whole time that you see that there's force on the ball?

- 12 **Denise:** Um...
- 13 **Teacher:** Will you just use your finger to show me where you think there's force on the ball on the graph? [Diana points to the whiteboard (video is not clear enough to determine what she's pointing at)].
- 14 **Denise:** OK. For five, draw two pictures of the ball to show what forces are acting on the ball. OK. Well, when the person is kicking it, the ball is receiving the force, so the force is going towards the ball. But after the guy is done kicking it, the force leaves the ball. So, that's why the arrows are coming out.
- 15 **Teacher:** Thank you. Thank you very much, group number six. May I see that whiteboard? Wonderful. Thank you. Alright, group number five. [Group five gets up] So, group five had some incredible discussion, and I didn't catch all of it, but will you guys be sure to share some of the discussion that you had, or the debate as you called it for question three.
- 16 **Aron:** Alright. [Inaudible banter between Sergio and Diana].
- 17 **Teacher:** Alright, go ahead.
- 18 **Aron:** Alright, I thought that, uh, this is their drawing [points to graph on whiteboard]. I thought that, uh, there would be no force after the dude kicks it, because there's a difference between force and energy, so the force applies the energy, and then just gives it the energy, and it slows down. It loses the energy. And they [inaudible].
- 19 **Antonio:** We were thinking that the whole time the ball moves it's the force moving the ball so that the whole time it's moving like the force made it move so that's how it stops because the force on the ball stops. So, we were debating if it's gravity is what is friction is what makes it slow down. So we were debating if gravity and friction is a force as well.
- 20 **Teacher:** Sorry, will you say that one more time?
- 21 **Antonio:** We were having a debate whether friction or gravity was a force as well.

- 22 **Teacher:** That's a good question, and we will investigate throughout this chapter. Are gravity and force--I'm sorry. Are gravity and friction forces? Good question. You guys really fleshed out a lot of ideas. Like you brought energy into it. You really thoroughly talked about that question number three. I'm very impressed. Will you share your question number five?
- 23 **Erin:** Well, I think there's a [inaudible] was a force, so I didn't really know.
- 24 **Doug:** We didn't know if there's a second, um, push.
- 25 **Teacher:** So you--Sorry, I want to make sure I hear all the rest of Erin's thoughts but, really fast, you weren't sure if there was a second push.
- 26 **Doug:** Yeah, we know there's a push going to the ball with the, I guess, kicking it, but we weren't sure if there was like after if there was still a force after the kick.
- 27 **Teacher:** OK. Very interesting. Erin, did you get to say everything you wanted.
- 28 **Erin:** Yeah.
- 29 **Teacher:** Yeah? OK. Very nice. Thank you very much group number five. Group number four.
[Group four gets up]
- 30 **Osbaldo:** For question three, we said that there was a force acting on the ball until like [inaudible] kicks it. We said that right here where he kicks it that's where the force stops. We said like, there has to be another force acting on it that makes it slow down...like friction or gravity or other force that slows it down and stops it. [inaudible sentence]. Right here we showed that [inaudible] a force [inaudible]. The kick adds a force to it and right here there's a force that makes it slow down.
- 31 **Teacher:** Awesome. Very nice. Thank you so much for sharing. Alright, group number three.
[Group three gets up. Diana pokes fun at their drawing; it is well received]. Alright, please give this group your attention.
- 32 **Richard:** So, for three, we just thought that [inaudible] forces [inaudible]. [graph is a trapezoid with small side on top].

- 33 **Devante:** And on five its like the force is where the ball is kicked and then like the ground or the grass is like the friction which causes it to slow down.
- 34 **Teacher:** Awesome. Thank you so much group number three. [inaudible] Group number two.
[Group number two gets up]
- 35 **Chris:** So, for question number three we thought that the contact interaction was gave it it's force and that it didn't have any...it was just a constant in the air and once it hit the grass there was a decrease in speed or velocity-however you interpret that. And then, yeah.
- 36 **Teacher:** Sorry. I'm sorry. I got a little bit distracted. Will you show me with using your finger on your graph where you thought there were forces?
- 37 **Chris:** I thought there was a force right here [the first zero of the graph] and there was also a force right here [the end of the flat top]. the first force was the kick, obviously. And then I think there was a force [inaudible] it was in the air or whatever. And then the second force was a decrease in speed like friction from the grass or the ground or whatever it landed on.
- 38 **Teacher:** Thank you very much. And question five.
- 39 **James:** First the player kicks the ball which is a contact interaction, which drives the ball forward over the grass [inaudible]. Then it makes contact again, which slows it down and notice the decrease in speed [inaudible].
- 40 **Teacher:** Thank you so much. Group number one. [Group one gets up] Alright, let's give group number one our full attention.
- 41 **Doug:** OK, so for number three we drew a little graph right here. We thought the force was right here and right here [points to the upward and downward sloping portions of what looks like a bell curve] also too, right [looks to Claudia].
- 42 **Sonia:** Yeah, the foot exerts a force to the ball. That's what causes it to go up. It's adds a [inaudible] that needs a force to bring it down. And that's [inaudible] the ball [inaudible] something pushing or bringing it down.

- 43 **Doug:** And for number five, I thought um, the force was that way and the force was that way
[points to whiteboard; cannot tell what is on the board]. they interact with the ball so I feel like the
contact overcame the force due to gravity. the second one the friction from the grass helped slow it
down [inaudible].
- 44 **Teacher:** Awesome. thank you so much. Is that everything?
- 45 **Doug:** Yeah.
- 46 **Teacher:** Wonderful. So, I am really impressed with how far we've come as a classroom
community. Here's what I saw. For one, I saw everybody listening to their peers.



CHAPTER 5

Developing Ideas



ACTIVITY 1: Electric Circuit Interactions--KEY

Purpose

Many practical devices work because of electricity. In this first activity of the Cycle you will first focus your attention on a simple circuit, consisting of a battery and a bulb. When the bulb is connected to the battery and it lights, we say that there is an *electric circuit interaction* between the battery and bulb. For the bulb to light, however, does it make any difference *how* the battery is connected to the bulb? Does it make any difference what *kinds of materials* are used to connect the battery and bulb? As you work through this activity, you will investigate the simple electric circuit and develop answers to these questions. Then you will take apart a flashlight to see how it works.



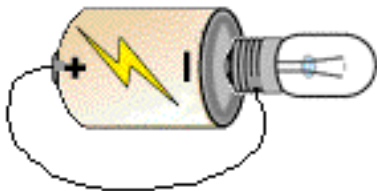
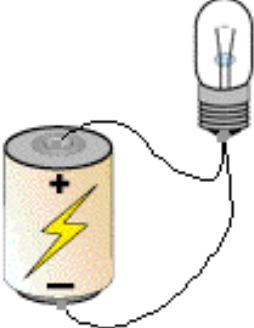
What conditions are necessary for an electric circuit to work?

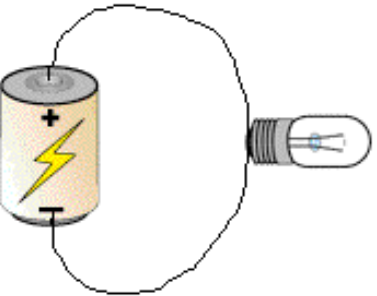
Initial Ideas

Imagine that you had a battery, a small bulb and some wires. You were curious about what arrangements would cause the bulb to light. On the following page are pictures of six possible arrangements, with brief descriptions of how the wires are connected in each case. Look at each arrangement carefully and **predict** whether that particular arrangement would cause the bulb to light. **Do this individually at first before discussing it with your group.**



Write “YES” next to **Pred:** for each arrangement that you think would light the bulb. Write “NO” next to **Pred:** for each arrangement that you think would not light the bulb.

#1 The tip of the bulb touches the negative end of the battery. A wire touches the negative end of the battery and the positive end of the battery. Pred: Obs: No	 #2 The tip of the bulb touches the negative end of the battery. A wire touches the positive end of the battery and the metal side of the bulb. Pred: Obs: Yes	 #3 One wire touches the positive end of the battery and the tip of the bulb. A second wire touches the negative end of the battery and the tip of the bulb. Pred: Obs: No
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#4 The tip of the bulb touches the positive end of the battery (but not the knob in the middle). A wire touches the metal side of the bulb and the negative end of the battery. Pred: Obs: Yes	 #5 A single wire touches the positive end of the battery and the negative end of the battery. The tip of the bulb touches the middle of this wire. Pred: Obs: No	 #6 The metal side of the bulb touches the positive end of the battery. A wire touches the tip of the bulb and the negative end of the battery. Pred: Obs: Yes
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What criteria were you using in making your decisions? That is, what did you think was necessary for the bulb to light?

It is not uncommon for many students to choose #1, #3 and #5 setups as the ones where the bulb will light. In all of these the tip of the bulb is connected to the knob end of the battery or the wire. Students often don't recognize that the side of the bulb must also be connected, and they don't usually have a sense of the problematic nature of a short circuit.

"The bulb will light as long as there is something touching both ends of the battery, whether the wire or the bulb itself."

"To see if the battery has contact with the wire, and the wire has contact with the bulb."

Discuss your answers and reasons with your group members. If you change your mind, do not erase your original answer, but instead just add the opposite answer alongside your original answer.

Collecting and Interpreting Evidence

Experiment #1: What conditions are necessary to light the bulb?

Each student will need: ▶ One

battery

▶ One bulb

▶ Two bare copper wires

▶ Other items (switch, bulb holder, battery holder and three hook-up wires) to be picked up during STEP 3 below

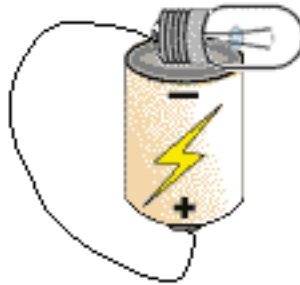
STEP 1. Try each of the six arrangements pictured on the previous pages. In some cases you will need another group member to assist you to hold all the pieces together.

 Write “YES” next to **Obs** (for Observation) for each arrangement that actually lights the bulb, and write “NO” next to **Obs** for each arrangement that does not light the bulb.

 Which of the setups use a battery, bulb and a single wire and the bulb lights? Setups #2, 4 and 6.

STEP 2. Figure out one more different arrangement of battery, bulb and a single wire that lights the bulb.

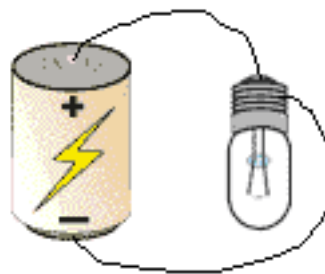
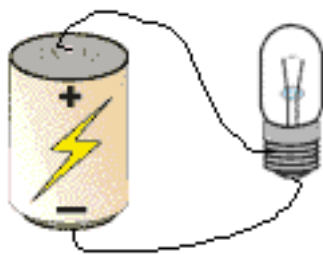
 Draw a sketch of your new successful arrangement.



The side of the bulb touches the negative end of the battery. A wire connects the tip of the bulb and the positive end of the battery.

STEP 3. Figure out an arrangement using the battery, bulb and two wires that light the bulb.

 Draw the circuit below.



In which of the setups from the *Initial Ideas* question does a wire directly go from the positive to the negative end of the battery without touching the two parts of the bulb?

#1, #3, and #5

Did the bulb light in any of those cases?

No

In those cases did you notice if the wire got warm?

Yes, especially in #1 and #5



Look over all the arrangements that allow the bulb to light, and answer the following questions.

Which part or parts of the **battery** need to be part of the connections?

Both the positive and negative ends of the battery.

Does a wire or part of a bulb need to touch the positive end of the battery only where the knob is, or can it touch any place on the positive end of the battery away from the knob?

It can touch anywhere on the positive end of the battery, not necessarily on the knob.

Which part or parts of the **bulb** must be touched to make the bulb light?

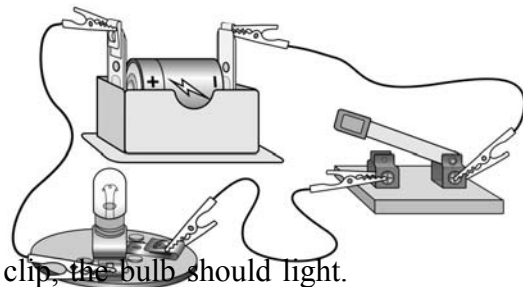
Both the screwy side and the bottom tip.

STEP 3. It is awkward to hold the battery, wires and bulb together to build circuits. To make things easier, there are special holders for the battery and for the bulbs, and special hook-up wires that have ends that are easy to attach. There is also a switch to make it easier to open and close the circuit.

Get a battery holder, bulb holder, switch and three hook-up wires with small alligator clips on their ends. Snap the battery into its holder, and screw the bulb into the bulb holder. Use the three hook-up wires and connect the circuit together with the switch.

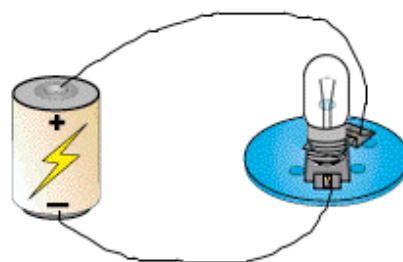
With the handle of the switch down between the clip, the bulb should light.

The circuit is said to be “closed.” When the handle is lifted up, the bulb should stop glowing, and the circuit is “open.”

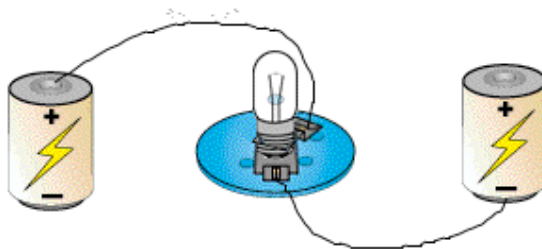


Experiment #2: How do the two ends of the battery need to be connected to the two sides of the bulb?

The evidence from Experiment #1 suggests that one side of the bulb needs to be connected to the positive end of the battery, and the other side of the bulb needs to be connected to the negative end of the battery.



But do the two sides of the bulb need to be connected to the positive and negative ends of the **same** battery? Consider the following arrangement:



Do you think the bulb in the above arrangement will light? Explain your reasons.

“Yes, because positive current comes from the positive end of the battery to the bulb, and negative current comes from the negative end of the battery to the bulb. Since it has currents from both ends of the battery, the bulb will light.”

“Yes, because the energy will flow from one battery to the bulb and into the other battery. This creates a circular pattern of energy.”

“No, there is not a complete circuit”

“No, the circuit has to be connected”

If students have a strong two-flow model (thinking that electricity flows out of each end of the battery towards the bulb), they may predict that the bulb should still glow. They know from the previous experiment that both ends of the battery need to be involved in making the bulb light. However, they may only focus on the “endedness” of this criterion, not on the fact that the two ends must be part of the same battery. Even with a two-flow model they may think that there needs to be a complete circuit, so they could predict that this bulb would not glow. If they have a one-flow model (thinking that electricity flows one way around the circuit) they should predict that the bulb would not glow.

Get two batteries, two hook-up wires and a bulb in a socket. Hook up the arrangement shown above.



Does the bulb glow?

No



Do the two ends of the bulb need to be connected to the two ends of the **same** battery for the circuit to work?

Yes

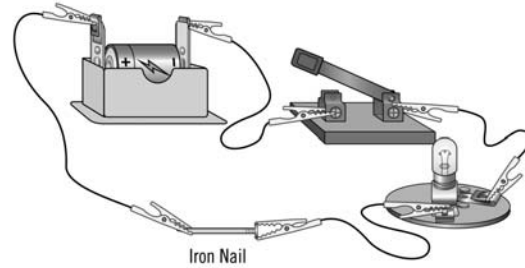
Experiment #3: What kinds of materials are necessary for an electric circuit to work?

In the previous experiment you used copper wires to connect the battery and bulb together. (At first you just used bare copper wires. Then, to make it easier to connect things, you used special copper wires with a surrounding plastic sheath and metallic alligator clips at its ends.) Does it make a difference what kinds of materials you use to connect the battery with the bulb? Will anything work to allow the bulb to light? You will try to answer those questions in this experiment.

Your group will need:

- ▶ One battery in battery holder ▶ One bulb in bulb holder
- ▶ Switch
- ▶ Four hook-up wires
- ▶ Various items made of different materials, like an iron nail, wood stick, glass rod, aluminum foil, copper strip, steel nut, etc.
- ▶ Bulb with glass removed
- ▶ Magnifier

STEP 1: Construct a circuit similar to the one shown in the picture. The iron nail is placed in the circuit. At the start the switch handle is up. Close the switch.



 Does the bulb light? Record your observation in the Table on the next page.

STEP 2: Open the switch and remove the iron nail. Replace it with another item from the bag. Attach the two free alligator clips to the two ends of the item. Then close the switch.

 Record your observations in the Table on the next page about whether the bulb does or does not light.

STEP 3. Repeat step 2 for all of the other items that you gathered.

 Record your observations in the Table.

STEP 4. Try two or three additional items to see whether they will allow the bulb to light.

 Add your observations to the Table.



What seems to be common about the types of materials that need to be included in the loop of an electric circuit so the bulb will light?

“They all seem to be some type of metal”

Materials that can be included in a circuit to light the bulb are called **conductors**.
Materials that do not allow the bulb to light when included in a circuit are called **insulators**.

Table: Materials that allow the bulb to light

Item and material	Does the bulb light? (YES or NO)
iron nail	"Yes"
wood stick	"No"
glass rod	"No"
aluminum foil	"Yes"
copper strip	"Yes"

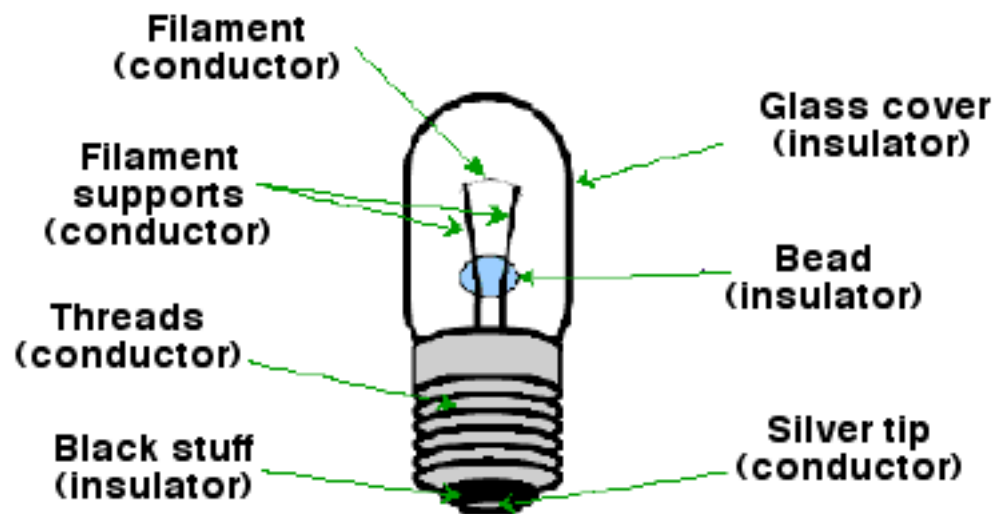
steel nut	"Yes"
air	"No"

STEP 5. Hook up the circuit with the battery and bulb. Close the switch so the bulb glows. Look closely at the bulb through the magnifier.



Which **part** of the bulb is actually glowing? (See picture below for the names of the various parts.)
The filament.

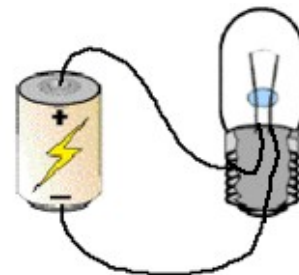
Below is a sketch showing the various parts of a bulb, and whether each part is a conductor or an insulator.



STEP 6. Look closely inside a bulb that has its glass cover removed. Use the magnifier if necessary. Play particular attention to what happens to the two filament support wires in the base of the bulb.



To the right is a picture of a battery, bare bulb (cut-out view) and two wires. By connecting lines, show how the two filament support wires are connected to the two wires from the battery.



Starting at one end of the battery, describe in words the sequence of parts (both outside and inside the bulb) that form a continuous pathway of conductors from one end of the battery to the other. Use terms like *wire*, *filament support wire*, *filament*, *side of bulb* and *bottom tip of bulb*.

Starting at the positive end of the battery, there is a wire connecting the positive end to the side of the bulb. Inside the bulb, one filament support wire connects the side of the bulb to one end of the filament. Another filament support wire connects the other end of the filament to the bottom tip of the bulb. Finally, a wire connects the bottom tip of the bulb to the negative end of the battery.

Experiment #4: What are two ways of connecting two bulbs to a battery?

You group will need:

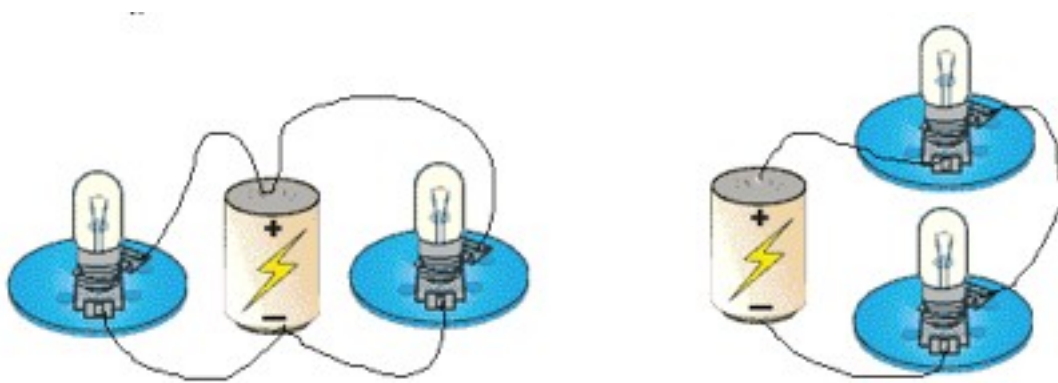
- One battery in battery holder Two bulbs in bulb holders
- Switch
- Four hook-up wires

Your task is to figure out two different ways of connecting two bulbs to a battery, subject to the following conditions:

1. In the first arrangement, the two bulbs glow equally as bright as a single bulb connected to a single battery. Furthermore, when either of the two bulbs is unscrewed from its socket, the other bulb remains lit at the same brightness.

2. In the second arrangement, the two bulbs glow equally, but each is much less bright than when a single bulb is connected to a single battery. Furthermore, when either of the two bulbs is unscrewed from its socket, the other bulb goes out (it no longer glows).

After you are successful at constructing each of these two arrangements, sketch diagrams of them below.



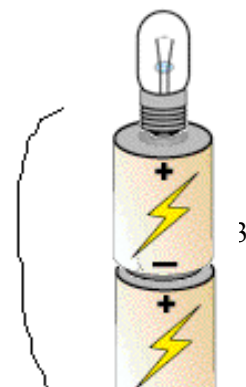
The first arrangement is called a **parallel** (or multiloop) circuit, and the second arrangement is called a **series** (or single loop) circuit.

Experiment #5: (Optional) How does a flashlight work?

You will need:

- ▶ Flashlight that can be taken apart--the flashlight may have either a plastic or metal casing.
- ▶ Two Batteries, one bare bulb and one bare copper wire.

STEP 1. Two members of your group should work together to connect two batteries, a bulb and a bare copper wire as shown to the right.





What do you need to do to make the bulb light?

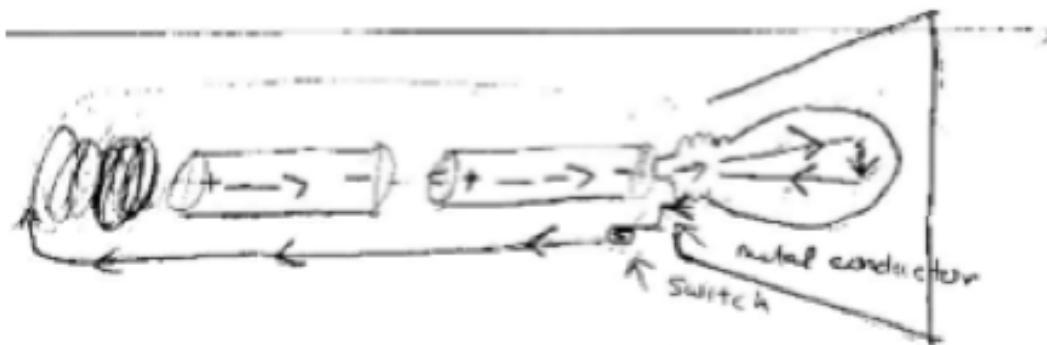
Touch the loose end of the wire to the side (screwy) part of the bulb.

This arrangement can be thought of as a very simple flashlight. However, to turn this flashlight on and off requires you to alternately touch the free wire to the side of the bulb and then pull it away. That's not very convenient. A regular flashlight does this in a clever way.

STEP 2. Examine the regular flashlight with your group. Take it apart and figure out how it works.

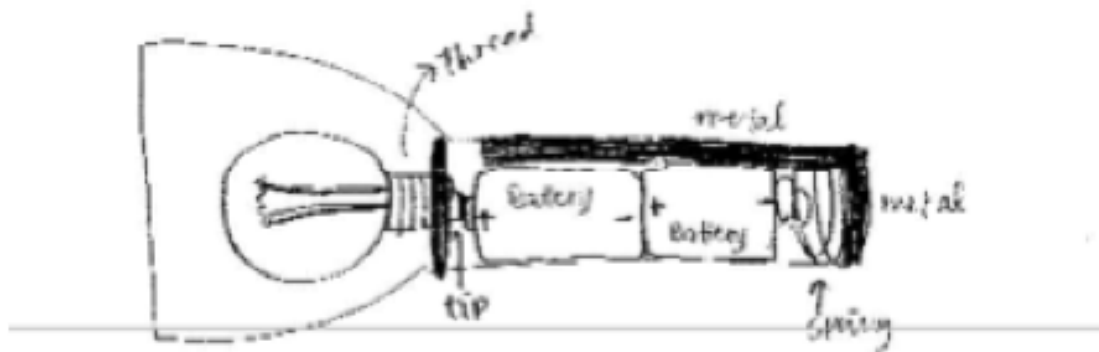


Draw a picture of the various electrical parts of the flashlight and show how they are connected together. Use a different colored pencil to trace the path of conductors around the entire circuit. Write a few sentences to explain how the flashlight works—that is, what actually happens when you slide the switch and the light goes on.

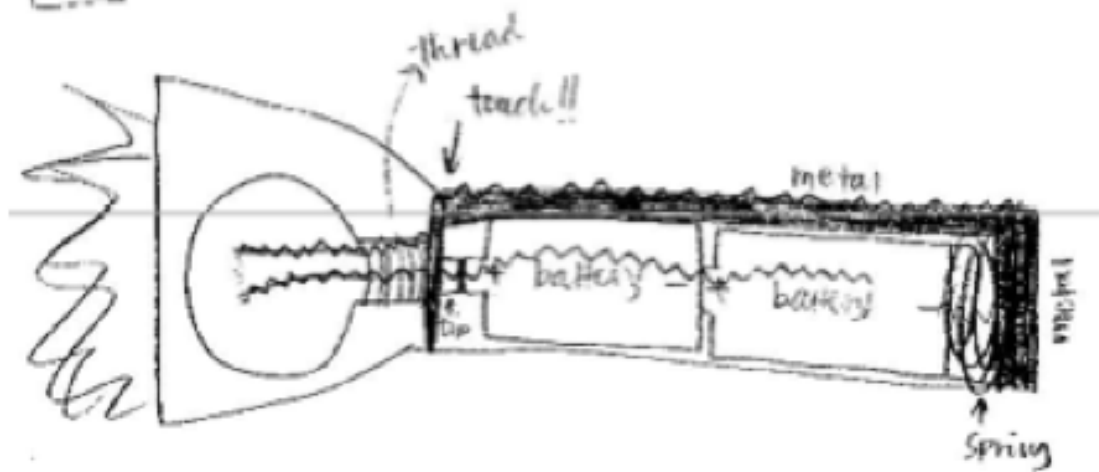


The arrangement of the batteries, coil at bottom, bulb, switch, and side of battery casing (if metal) forms a complete electrical circuit when the switch is 'on'. Electric energy flows through the batteries, causing the bulb to light. When the switch is "off" - the metal conductor is separated from the side of the bulb, breaking the circuit and causing the light to turn off. (In this metal flashlight, the ^{metal} casing itself conducts the electric energy back to the coil)

off



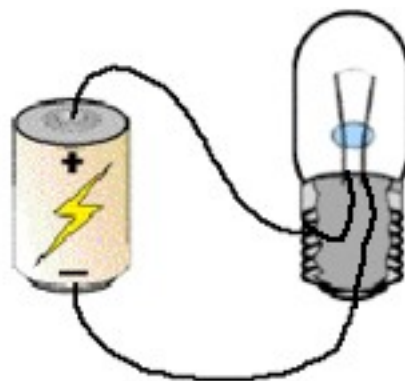
on



Draw your sketch on a discussion board and mount it so other groups can see it. When they are ready, walk around the room and look at the other groups' drawings. If you find a diagram much different from your own, discuss those differences with the other group(s).

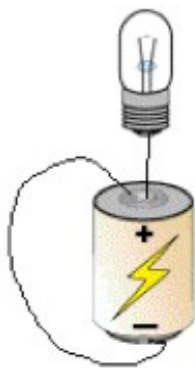
Summarizing Questions

S1. Draw a continuous line that shows the pathway of conductors from one end of the battery, through the bulb, to the other end of the battery. As you did in Step 3 of Experiment #3, be able to describe in words the different parts of the pathway.

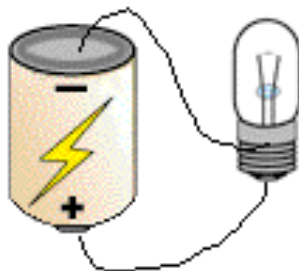


Starting at the positive end of the battery, there is a wire connecting the positive end to the side of the bulb. Inside the bulb, one filament support wire connects the side of the bulb to one end of the filament. Another filament support wire connects the other end of the filament to the bottom tip of the bulb. Finally, a wire connects the bottom tip of the bulb to the negative end of the battery.

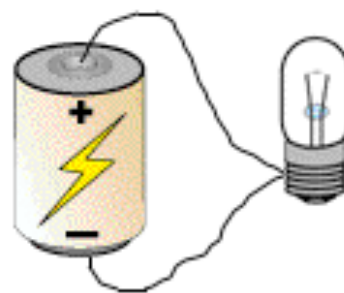
S2. The pictures below represent three different ways of putting together a battery bulb and one or more wires. In each case indicate whether the bulb will light or not light. Justify your choice in terms of the ideas developed in this activity (i.e. the conditions necessary to light a bulb).



(a) ne wire touches the positive end of the battery and the tip of the bulb. A second wire touches the positive end of the battery (not the knob in



the middle) and the negative end of the battery.



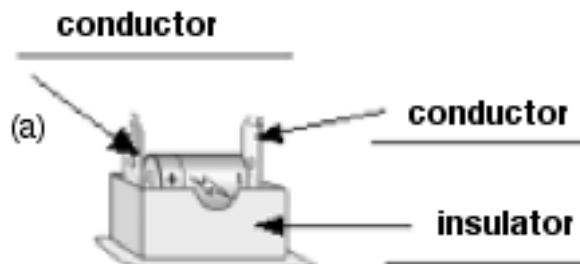
(b) One wire touches the negative end of the battery and the metal side of the bulb. A second wire touches the positive end of the battery and the tip of

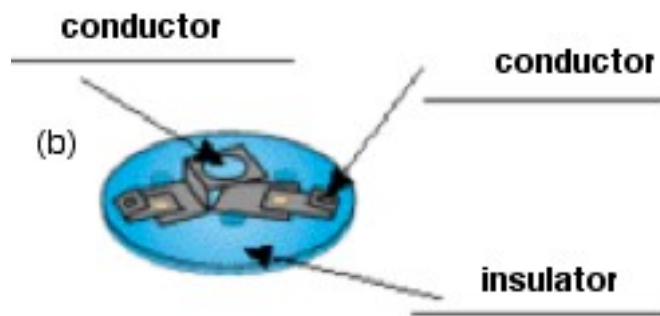
the bulb.

(c) One wire touches the positive end of the battery and the metal side of the bulb. The other wire touches the negative end of the battery and the metal side of the bulb.

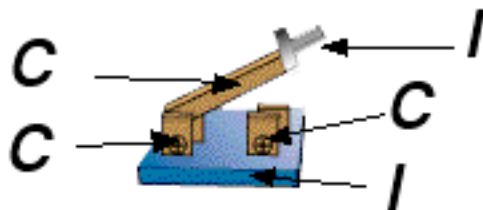
- (a) The bulb will not light because both side of the bulb are not connected in the circuit to both sides of the battery.
- (b) The bulb will light because one side of the battery is connected to one side of the bulb, and the other side of the battery is connected to the other side of the bulb.
- (c) The bulb will not light because both sides of the bulb are not connected in the circuit to both sides of the battery.

S3. Below are pictures of a battery holder, bulb holder and switch. Several parts of these components are identified. Indicate whether you think each part is a **conductor** or an **insulator**. Justify your answers.





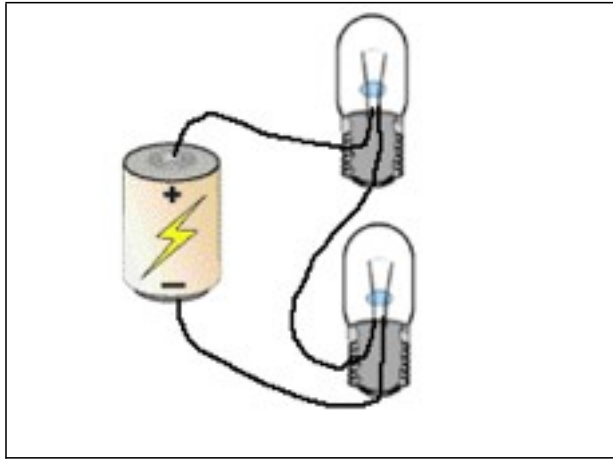
(c)



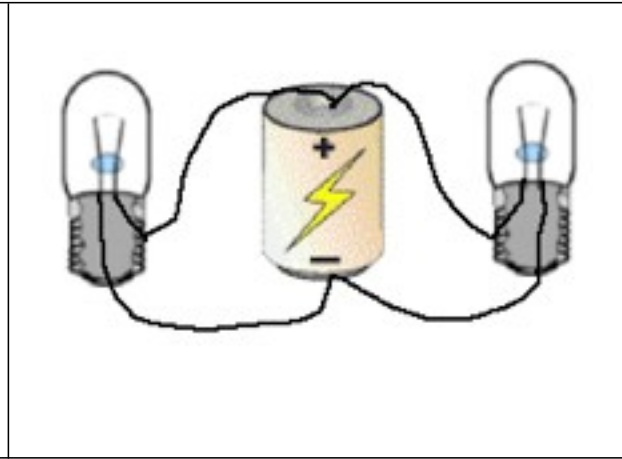
S4. In Experiment #4 you constructed two different circuits, each with a battery and two bulbs. Assume that each bulb is in a bulb socket.

Redraw the two circuits below, but make the bulb and socket large enough in each case to explicitly show the different parts of the socket and the filament support wires and filament in each bulb. Using a different color pen or pencil, trace a conducting path (or paths) from each end of the battery, to each socket, through the inside of each bulb, and then to the other end of the battery.

[Note: To make the pathways easier to see, the bulb sockets have been left out of the pictures of the two circuits below. One clip on the bulb holder connects directly to the bottom tip of the bulb, and the other clip connects directly to the screwy side of the bulb.]



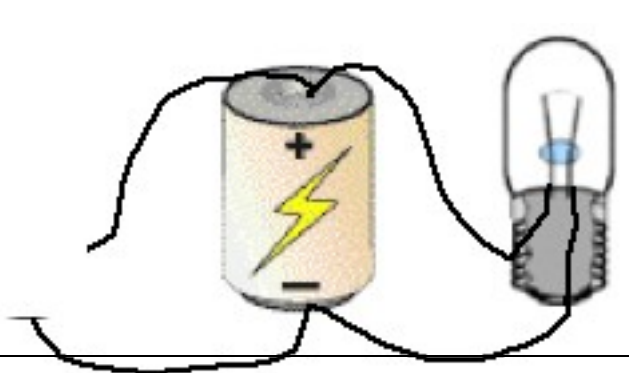
Series Circuit



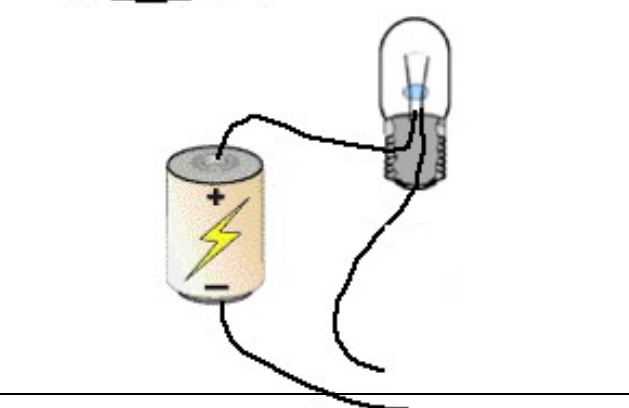
Parallel Circuit

S5. Consider the same two circuits you drew above. **Write a scientific explanation for why (a) in one case, when a bulb is unscrewed from its socket, the other bulb remains lit. (b) Also explain why in the other case, when a bulb is unscrewed from its socket, the other bulb goes out.** For each case, your explanation should include a diagram of the circuit with one bulb unscrewed from its socket, and a written narrative for why the other bulb either continues to be lit or goes out. Your diagrams should be large, like the ones you drew in S4.

(a) If you remove the left bulb in the parallel circuit, the bulb on the right is still part of a complete circuit—there is a continuous conducting pathway from one end of the battery, through the right bulb, to the other end of the battery. Therefore, the bulb on the right still glows.



(b) If you remove the bottom bulb in the series circuit, however, there is no longer a continuous conducting path from one end of the battery through the bulb, to the other end of the battery. Therefore, the remaining bulb will not light.



 Participate in a whole class discussion about answers to the above questions.

APPENDIX C: Full analysis of teacher facilitation of Electric Circuit Interactions activity

Analysis 3 – How does the teacher facilitate learning in this CIE task?

The video segment from the previous section is again analyzed here to determine how the teacher facilitates student learning. Specifically, what pedagogical moves does the teacher make to guide student sense-making and inductive reasoning? We begin with the students starting Experiment 2 in which they are attempting to light the bulb with the configuration shown here in Figure 6.

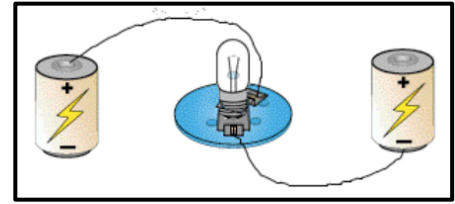


Figure 6. Experiment 2

- 26 **Sonia:** Wait, let's try it again. [Manuel touches the wire coming off one side of the bulb and places it on the positive terminal of the battery]
- 27 **Sonia:** You're doing the positive, you idiot! [laughs]
- 28 **Manuel:** Oh. Ah! It (the wire) came out! [Manuel stands and continues to help. Sonia continues tinkering. Teacher comes around the table to get a closer look at what Sonia is doing.]
- 29 **Teacher:** Is that what you expected? [to Sonia]
- 30 **Sonia:** I was expecting it to light. Um, not gonna work.
- 31 **Teacher:** That's interesting because here [as shown in Figure 4.8 below, the teacher points to the diagram shown on the right] it's going from a positive to a negative and you set it up to go to a positive to a negative. So what's the difference between what like you set-up in this one or this picture?

Note: Figure 4.13 does not show a completed circuit, because the wires are not touching the bulb correctly. It was likely used here by the teacher to show two wires connected to the poles of one battery in an apparent loop. Of the six diagrams in Figure 4.4, the teacher may have decided that this one most clearly shows the components forming a loop.

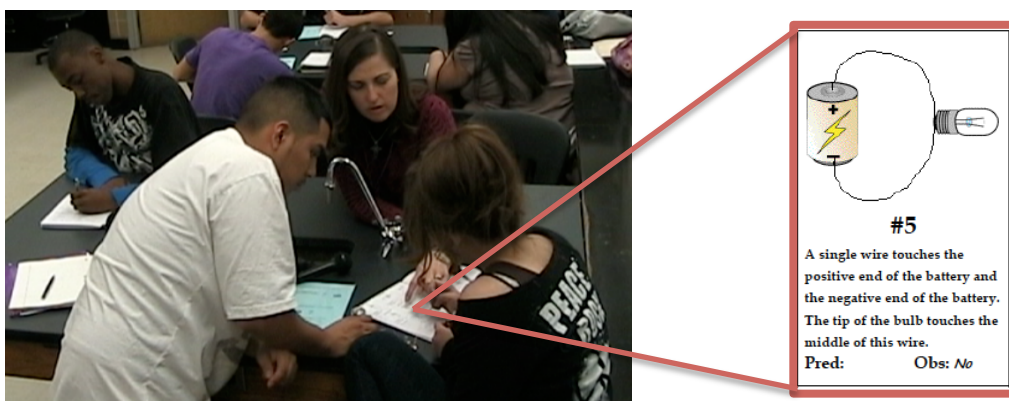


Figure 4.13. The teacher pointing to a circuit diagram.

Upon seeing that the students are perplexed by the failure of the bulb to light in this configuration, in line 31 above the teacher draws their attention to a diagram (Figure 4.13) showing a circuit with two wires that are connected to the poles of the same battery (note again that this is not a complete circuit). She then asks the students what the difference is between their set-up and the circuit in the diagram. Below, Manuel explains that the set-up should light the bulb.

32 **Manuel:** Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know? And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that (points to something on the apparatus that is hidden from the camera).

33 **Teacher:** Interesting.

34 **Manuel:** And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up. [Other students are toggling the overhead lights, presumably so that they can see if their bulbs are lit.]

35 **Teacher:** Interesting, so you have...Hey guys (to other students), since we're all in different pieces of the lab, go ahead and keep the lights on. OK? Thank you. So, yeah, that's really interesting. How? You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said "check." Alright, it's going from the positive end of one to the negative end of another, but it's still not working. So, what's the difference between what you set up here with these two batteries and

36 **Sonia:** The wires aren't directly touching the light bulb.

37 **Teacher:** OK, the wires aren't directly touching the light bulb. Do you wanna try it by taking the wires out and have...[Students try taking the wires out.]

[Dion and The teacher have a short side conversation about other ways to connect the wires.]

48 **Sonia:** Alright. [The group looks and sees that the bulb did not light in this configuration either.]

Above in lines 32 and 34, Manuel explains that the wires are connected correctly to the bulb and asserts that “it should light up.” The teacher responds to his assertions in lines 33 and 35 with the comment, “interesting.” The teacher then recounts Manuel’s assertion that the wires are connected to the bulb correctly in line 35 (consistent with the students conclusions from Experiment 1) and again begins drawing the students’ attention to the differences between the current configuration and the configuration above in Figure 4.8. At this point, Sonia poses another difference between the configurations in line 36, and the teacher asks if they want to try it. The students try this configuration, and it does not light the bulb. Below, the teacher again prompts the students to examine the set-up in Figure 4.8 and their current configuration for some difference.

49 **Teacher:** Huh. So, here's my question for you: What's the difference between what you have going on here in this picture...

50 **Sonia:** Oh, this one isn't touching...the light bulb isn't touching the battery.

51 **Teacher:** That's true. So, that's a difference from here. And look at these two different pictures. We have this picture with one battery going from the plus to the minus. And then this one (bulb goes from bulb to +terminal of one battery and to -terminal of another battery, shown in lower Figure 4.14) ...

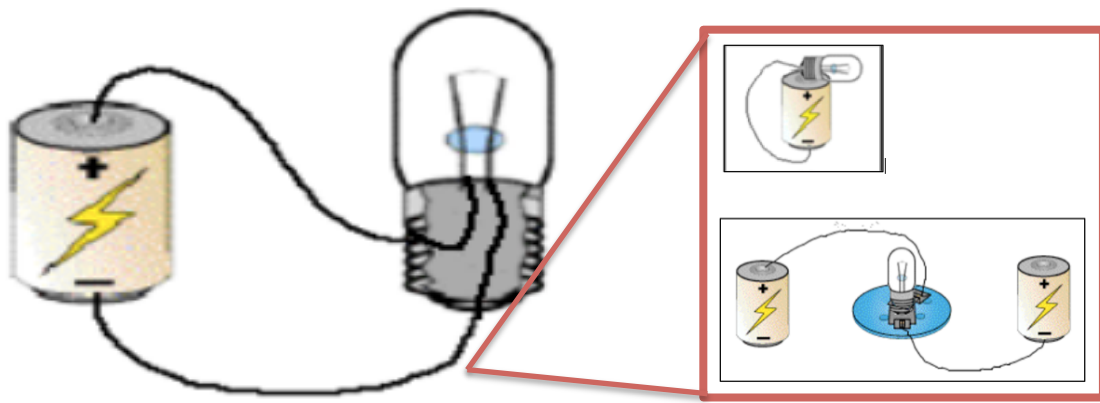


Figure 4.14. Teacher attempting to draw students' attention to differences.

- 52 **Sonia:** Oh.
- 53 **Teacher:** What's the difference between those two set-ups that you made?
- 54 **Sonia:** There's two batteries.
- 55 **Teacher:** So, this one has two batteries.
- 56 **Sonia:** It's not getting the whole circuit.
- 57 **Teacher:** What do you mean when you say circuit?
- 58 **Sonia:** It's supposed to make like, like it's a circle of life [traces a circle on the paper with her finger].
- 59 **Teacher:** Oh, interesting. That's interesting.

Above, as Sonia tries to determine why the configuration shown in lower Figure 4.14 will not light, the teacher continues to ask what the difference is between the set-ups (one is a complete circuit, the other is not) in line 49. The teacher then becomes more specific, drawing attention in line 51 to the fact that the set-up in upper Figure 4.14 is connected to only one battery, whereas the one in lower Figure 4.14 is connected to two batteries. Again, she asks what the difference between the two set-ups is in line 53. In line 56, we see evidence that Sonia sees the crucial difference between the two set-ups when she says, "It's not getting the whole circuit." The teacher then asks what she means by "circuit" in line 57 and then comments, "Oh, interesting. That's interesting." Sonia continues her explanation below.

- 60 **Sonia:** That's how you're supposed to...There supposed to connect each other and, like,
either these have to be touching like that [puts batteries in series stacked end to end])
and then one wire would have to come from here and the other one from here and then
connect to this and that would probably...
- 61 **Teacher:** You wanna try?
- 62 **Sonia:** Yeah.
- 63 **Teacher:** OK. So, you just found a key difference and I'm...so let's double test...let's
double-check that we could still do it with two batteries as you propose in your method.
And then we'll see if it has to be in a circle.
- 64 **Sonia:** I think it does because if it doesn't there's no circuit.
- 65 **Teacher:** Ah. So, you're saying for there to be a circuit, there has to be a circle.
- 66 **Sonia:** Yeah.
- 67 **Teacher:** Hm. Interesting. So, is this a circuit? [points to simple circuit on handout]
- 68 **Sonia:** Yes.
- 69 **Teacher:** And then [points to two battery setup in Figure 4.9]...
- 70 **Sonia:** No.

Above in line 60, Sonia continues to explain why the components must form a loop. In line 61, rather than evaluating Sonia's explanation, the teacher asks if the students want to test it. Note that in line 63, the teacher begins to tell Sonia that she "just found a key difference" but stops herself and continues encouraging the group to test it.

- 71 **Teacher:** Alright, let's try it with double battery.
- 72 **Sonia:** OK. Are those touching? [Sonia works with Manuel to hold the set-up. Dion
looks on. The bulb lights.]
- 73 **Sonia:** Ha!

- 74 **Teacher:** Ah, and what do you notice about that bulb compared to when you do it with one battery?
- 75 **Sonia:** It's um...
- 76 **Dion:** It's a lot brighter.
- 77 **Teacher:** It's brighter. Interesting. So, you just discovered a key compon...a key thing about electricity.

In line 72 above, the group tests it and the bulb lights. The teacher draws the students' attention to the brightness of the bulb resulting from the students using two two batteries in series in this circuit. The teacher then points out that the students have "discovered a key thing about electricity" in line 73.

In this episode we see that the teacher uses three distinct pedagogical strategies to guide the students through scientific induction. These strategies are:

1. Making benign comments that appear to affirm students' attempts to observe, infer, and explain without evaluating the students' ideas or explanations.

Example: "Interesting."

Evidence: Lines 31, 33, 35, 39, 67, 77.

2. Explicitly drawing students' attention to differences in apparatus configurations and associated observations with the intent of helping them develop accurate explanations.

Example: "What's the difference between those two set-ups that you made?"

Evidence: Lines 31, 35, 49, 33.

3. Deferring to the available laboratory evidence to determine the validity of students' ideas and explanations by encouraging students to test their assertions.

Example: "Do you wanna try it?"

Evidence: Lines 37, 61, 62, 71.

In this episode, the teacher appears to do very little to assist student sense-making and defers to laboratory evidence to sanction new knowledge. She resists the temptation to sanction the students' ideas (though not completely, as shown in line 63) and simply notes that students' ideas are "interesting." However, when she sees students not progressing, she employs the pedagogical move of drawing students' attention differences in apparatus configurations. When they recognize the answer, she suggests that they test it, thus deferring to students use of laboratory evidence to sanction new knowledge in the classroom.

APPENDIX D: Full analysis of the Case for Induction

Analysis 4 - The Case for Scientific Induction

In the previous section, I claim that *scientific induction*—the process of moving inferentially from the observation of concrete, specific instances of a phenomenon to an abstract, generally applicable principle—occurred. Given the centrality of induction to the PET curriculum (and not coincidentally to scientific inquiry more broadly), a more detailed analysis of the transcript evidence focusing solely on the evolution of students’ ideas toward and resulting in induction is warranted.

As is discussed above, students began this set of activities by making predictions in the Initial Ideas activity about the six battery-wire-bulb configurations shown in Figure 6.12. This activity is designed to elicit students’ ideas about batteries, incandescent light bulbs, and electrical circuits and was developed based on research on common student alternative conceptions.

The analysis of this transcript enters after these students have made predictions about and tested the six

configurations in Figure 6.12 in *Experiment 1: What conditions are necessary to light the bulb?*

Experiment 1 is designed to address the target idea that each device in a circuit has two ends and that each end must be connected directly in the circuit for electricity to flow.

Experimenting with the six configurations in Figure 6.12 leads the students to determine that three of the six configurations light the bulb. These are configurations two, four, and six, shown in

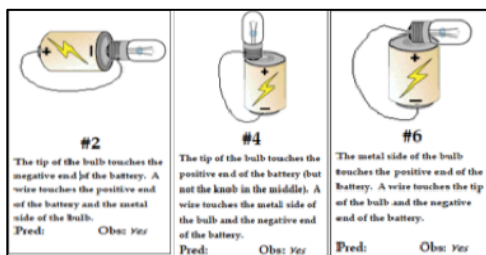


Figure 6.11. Configurations that light.

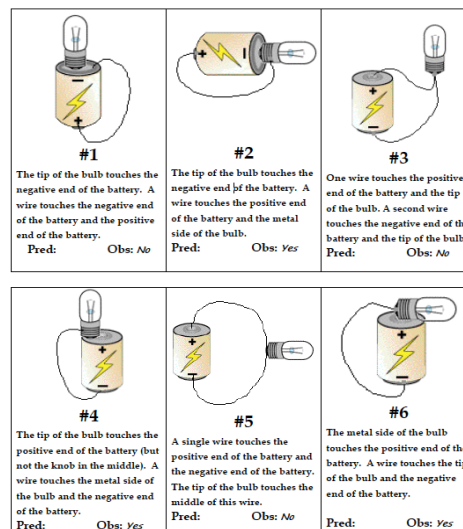


Figure 6.12. Initial Ideas, C5A1.

Figure 6.13. Perhaps the strongest evidence in the episode analyzed here that these students are progressing toward the target idea for Experiment 1 is that they connect the bulb correctly. But, as will be shown below, these students have developed the understanding that each end of a light bulb

must be connected to function, but have not yet come to the same conclusion about how a source, in this case a battery, must be connected. Of course, the idea that electrical components must be directly connected at each end in a circuit is conceptually equivalent to the idea that the components must form a complete loop, or *circuit*, in order for electricity to flow. However, the learner must recognize the generality of this idea—that this idea applies to any and all components in any electrical circuit—if one is to assert that scientific induction has occurred.

As Dion and Manuel are finishing up the questions for Experiment 1, Dion asks Manuel what the question is.

- 1 **Dion:** And what does question 8 say, Manuel?
- 2 **Manuel:** [Reading from his paper] Which part or parts of the battery need to be part of the connections? [Looks at Dion]. Like, like which part...[Sonia grabs handout and starts reading it] which part of the battery needs to be like part of...let's say like the positive. Let's say you have the battery, right?
- 3 **Dion:** Yeah.
- 4 **Manuel:** The positive is like, is touching like the bottom of the bulb and the negative wire is touching...
- 5 **Dion:** The side?
- 6 **Manuel:** Like the side or something. Or like how do you think it needs to be, you know.
- 7 **Dion:** Oh, the arrangement.

Above in lines 4 and 5, statements by Manuel and Dion suggest that it is plausible that they have determined how to correctly connect a light bulb.

Manuel, explaining the task to Dion in line 5 above, says, “The positive is like, is touching like the bottom

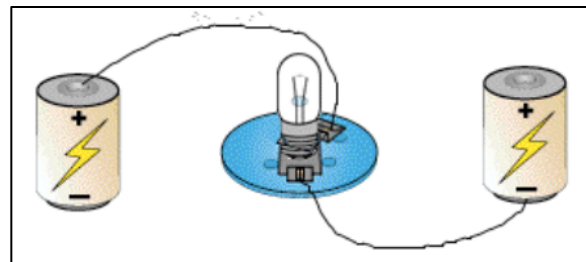


Figure 6.12. Experiment 2.

of the bulb and the negative wire is touching...” Dion completes the sentence with, “The side?”

suggesting that he understands how to correctly connect a bulb. It is unclear whether Manuel has yet to

understand this or if he is withholding the correct answer from Dion when he follows with “Like the side or something. Or like how do you think it needs to be, you know?” The question of their understanding is further confounded by the fact that in the experiment below the bulb is placed in a holder (shown in Figure 6.14) that connects the bulb correctly for the students.

Probable Conceptual Status: The bulb must be connected with one wire touching the side and one touching the bottom (accurate).

After some bickering about who will be in primary control of the apparatus, Sonia and Manuel begin experimenting with the configuration in Figure 6.14 for *Experiment 2: How do the two ends of the battery need to be connected to the two sides of the bulb?*

- 20 **Sonia:** Alright...You get that one [Sonia places one of the two batteries in front of Manuel]. I get this one.
- 21 **Manuel:** Are you touching negative?
- 22 **Sonia:** Yeah, I'm [inaudible]. [Sonia continues tinkering while Manuel and Dion watch. The light does not light.]
- 23 **Manuel:** How about we change it? I do negative, you do positive. [Dion looks on as his lab partners experiment]
- 24 **Manuel:** What the fuck?! [Manuel drops the equipment and turns away from the task]. [Sonia continues tinkering, and Dion leans in and turns the handout toward him. After 7 seconds, Manuel turns back toward Sonia and looks at the handout. The teacher walks up to the table and begins watching/listening]
- 25 **Sonia:** Wait, let's try it again. [Manuel touches the wire coming off one side of the bulb and places it on the positive terminal of the battery]
- 26 **Sonia:** You're doing the positive, you idiot! [laughs]
- 27 **Manuel:** Oh. Ah! It (the wire) came out! [Manuel stands and continues to help. Sonia continues tinkering. The teacher comes around the table across from Sonia to get a closer look at what the students are doing. Again, the light does not light.]

28 **Teacher:** Is that what you expected?

29 **Sonia:** I was expecting it to light. Um, not gonna work.

The exchange above reveals that the group understands that a positive end of a battery and a negative end of a battery are necessary for a circuit to function. When the configuration in Figure 6.14 does not work, Manuel suggests that they switch each wire to the opposite poles of each battery. It is clear in line 24 that Manuel expected the bulb to light, indicating that he does not yet understand that each end of the same battery must be connected into the circuit for it to function. Sonia suggests that they try this configuration again, and realizes that Manuel is connecting his wire to wrong pole of his battery. That problem is corrected, and again the bulb does not light. In line 29, when Sonia says, “I was expecting it to light,” it becomes clear that she has not yet realized that the battery must be connected by both ends as well.

Conceptual Status: *The positive end of a battery and the negative end of a battery, though not necessarily the same battery, must be connected to the bulb for it to light (inaccurate).*

The teacher appears to recognize the consternation of the students and begins making direct pedagogical moves below.

31 **Teacher:** That's interesting because here [as shown in Figure 6.15 below, the teacher points to the diagram shown on the right] it's going from a positive to a negative and you set it up to go to a positive to a negative. So what's the difference between what you set up in this one or this picture?

Note: Figure 6.15 does not show a completed circuit. It was used here by the teacher to show two wires connected to the poles of one battery.

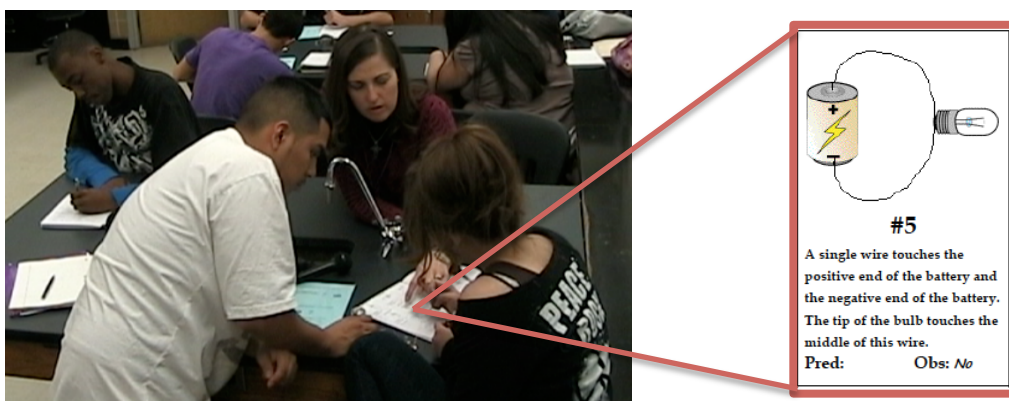


Figure 6.15. The teacher pointing to a circuit diagram.

32 **Manuel:** Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know? And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that (points to something on the apparatus that is hidden from the camera).

33 **Teacher:** Interesting.

34 **Manuel:** And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up. [Other students are toggling the overhead lights, presumably so that they can see if their bulbs are equally bright.]

35 **Teacher:** Interesting, so you have...Hey Guys (to other students), since we're all in different pieces of the lab, go ahead and keep the lights on. OK? Thank you. So, yeah, that's really interesting. How? You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said "check." Alright, it's going from the positive end of one to the negative end of another, but it's still not working. So, what's the difference between what you set up here with these two batteries and like...

36 **Sonia:** The wires aren't directly touching the light bulb.

37 **Teacher:** OK, the wires aren't directly touching the light bulb. Do you wanna try it by taking the wires out and have...[Students try taking the wires out.]

[Dion and Teacher have a short conversation about other ways to connect the wires.]

48 **Sonia:** Alright. [The group observes that the bulb did not light with wires connected directly to the bulb.]

In line 31, the teacher attempts to draw the students' attention to differences between their set-up (Figure 6.14) and the one she points to in Figure 4.15 showing a complete loop (though the bulb is not connected correctly). Manuel doesn't appear to acknowledge the teacher's move, and begins to explain why the bulb should have lit.

Manuel: Well, this doesn't make sense, because I think it should. **It should because metal is connected through it, you know?** And I think it like the negative charge should, uh, should pass all the... all the like electric charges through the, through that (points to something on the apparatus that is hidden from the camera).

Teacher: Interesting.

Manuel: And then **this one is like connected to the bottom so like the bottom of the bulb is touching the metal part** so I think it should light up.

Manuel's explanation suggests that he recognizes that there is a conductive path through the bulb. In his second statement above, he appears to be referring to the bulb holder and recognizes that the bottom of the bulb is connected to a wire through the holder. There is more evidence that Manuel is referring to the holder when the teacher says:

Teacher: You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said "check."

In other words, the teacher feels at this point that the students understand how to connect a bulb. Next, Sonia suggests that, in fact, the wires are not connected to the bulb through the holder. In line 36 she suggests that the wires need to be directly touching the bulb. They take the wires out of the holder, connect them directly to the bulb, and observe that it does not light. At this point, the evidence indicates that the students understand how the bulb must be connected, but do not yet understand that each end of the same battery must be connected into the circuit.

Conceptual Status: *The bulb must be connected with one wire touching the side and one touching the bottom (accurate). The positive end of a battery and the negative end of a battery, though not necessarily the same battery, must be connected to each end of a bulb for it to light (inaccurate).*

Again, the teacher attempts to draw the students' attention to recognizing one crucial difference between their set-up and another diagram on the students' paper, shown in Figure 6.16.

49 **Teacher:** Huh. So, here's my question for you: What's the difference between what you have going on here in this picture...

50 **Sonia:** Oh, this one isn't touching...the light bulb isn't touching the battery.

51 **Teacher:** That's true. So, that's a difference from here. And look at these two different pictures. We have this picture with one battery going from the plus to the minus (shown in upper Figure 6.16). And then this one (bulb goes from bulb to +terminal of one battery and to -terminal of another battery, shown in lower Figure 4.16).

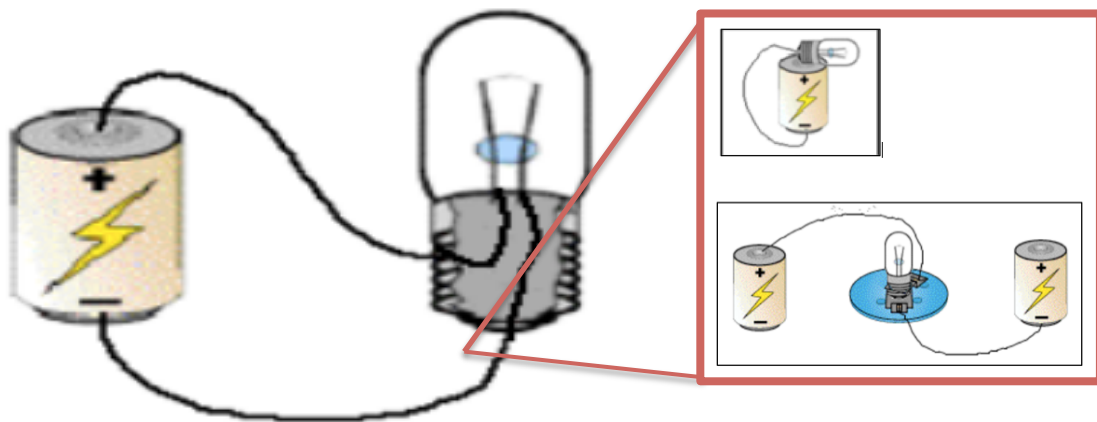


Figure 6.16. Teacher drawing students' attention to incomplete electrical path.

52 **Sonia:** Oh.

53 **Teacher:** What's the difference between those two set-ups that you made?

54 **Sonia:** There's two batteries.

55 **Teacher:** So, this one has two batteries.

56 **Sonia:** It's not getting the whole circuit.

- 57 **Teacher:** What do you mean when you say circuit?
- 58 **Sonia:** It's supposed to make like, like it's a circle of life [traces a circle on the paper with her finger].
- 59 **Teacher:** Oh, interesting. That's interesting.
- 60 **Sonia:** That's how you're supposed to...There supposed to connect each other and, like, either these have to be touching like that [puts batteries in series (stacked end to end)] and then one wire would have to come from here and the other one from here (the top of the top battery) and then connect to this (the bottom of the bottom battery) and that would probably...
- 61 **Teacher:** You wanna try?

The teacher points out the diagram in lower Figure 6.16, representing the students' apparatus, and upper Figure 6.15, showing a loop. Above in lines 50 and 54, Sonia points out two inconsequential differences between these configurations. Then in line 56, she recognizes the crucial difference and says "It's not getting the whole circuit." In line 58 and 60, she explains that the components need to form a circle.

There is more discussion of Sonia's conjecture in which the teacher verifies that Sonia is indeed talking about a complete circuit (not shown here). Below, the students test their hypothesis.

- 71 **Teacher:** Alright, let's try it with double battery.
- 72 **Sonia:** OK. Are those touching? [Sonia works with Manuel to hold the set-up. Dion looks on. The bulb lights.]
- 73 **Sonia:** Ha!
- 74 **Teacher:** Ah, and what do you notice about that bulb compared to when you do it with one battery?
- 75 **Sonia:** It's um...
- 76 **Dion:** It's a lot brighter.
- 77 **Teacher:** It's brighter. Interesting. So, you just discovered a key compon...a key thing about electricity.

- 78 **Sonia:** Ding, ding, ding [intermittently lights circuit (imitating a win on a game show.
All three kids laugh at the "ding" joke. Teacher leaves the group.]
- 79 **Manuel:** Nice!
- 80 **Sonia:** Yeah, high five [hi-fives Manuel then Dion] Uh! [emphatic] You better help me
find this out [laughs].
- 81 **Manuel:** Nice!

In line 73, the students verify through observation that their hypothesis is correct. They have inferred the circuit principle.

Conceptual Status: The positive end of a battery and the negative end of a battery must be connected to each end of a bulb for it to light. Each end of the components of an electrical circuit must be directly connected to the circuit, thus forming a complete loop, for electricity to flow.

The evolution of the group's understanding toward the target idea is inferred above from students' statements and actions. Students' statements provide the evidence from which student thinking was inferred. Students' actions, such as correctly connecting a light bulb, provide evidence for student understanding as well. Of course, no statement, action, or group of statements and/or actions can eliminate all uncertainty regarding students' conceptual understanding, but evidence is considered here in context and assertions about student understanding are made with the caveat that the content of these assertions is highly probable.

Each assessment of student understanding in the process of induction is presented in Table 6.5, along with the evidence supporting each phase of student understanding.

Table 5.5 Students' evolution toward general circuit principle.

<u>Conceptual Status</u>	<u>Supporting Evidence</u>
The bulb must be connected with one wire touching the side and one touching the bottom (accurate).	Manuel: “The positive is like, is touching like the bottom of the bulb and the negative wire is touching...” Dion: “The side?” Manuel: “Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know?” Manuel: “And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up.” Teacher: “You're right. So, you have...you know, you've tested this out. It's touching the bottom and the sides. So, like you said ‘check.’” In line 36 she suggests that the wires need to be directly touching the bulb. They take the wires out of the holder, connect them directly to the bulb, and observe that it does not light.
The positive end of a battery and the negative end of a battery, though not necessarily the same battery, must be connected to the bulb for it to light (inaccurate).	These students make several changes trying to get the bulb that is connected to the (+) of one battery and the (-) of another to light, including swapping the polarity and removing the bulb from the holder. At many points they express that they were expecting this configuration to light, as shown here: Sonia: “I was expecting it to light.” Manuel: “Well, this doesn't make sense, because I think it should. It should because metal is connected through it, you know?” Manuel: “And then this one is like connected to the bottom so like the bottom of the bulb is touching the metal part so I think it should light up.”

The positive end of a battery and the negative end of a battery must be connected to each end of a bulb for it to light.	Sonia: "It's not getting the whole circuit." Teacher: "What do you mean when you say circuit?"
The components of an electrical circuit must be directly connected on each end, thus forming a complete loop, for electricity to flow. <i>Note: These last two categories are distinct in that one specifically pertains to a battery, the other to all components. A distinction between these categories is not resolvable in these data.</i>	Sonia: "It's supposed to make like, like it's a circle of life." [traces a circle on the paper with her finger] Teacher: "Oh, interesting. That's interesting." Sonia: "That's how you're supposed to...There supposed to connect each other and, like, either these have to be touching like that [puts batteries in series (stacked end to end)] and then one wire would have to come from here and the other one from here (the top of the top battery) and then connect to this (the bottom of the bottom battery) and that would probably..."

The phases of student understanding and supporting evidence summarized in Table 6.5 provide insight into how these students' thinking evolved as they engaged the curriculum. Beginning with common student ideas about electrical circuits, the curriculum was carefully designed to guide students in collecting laboratory evidence and reconciling their current conceptions with that evidence. This group of students was led by the curriculum, with careful guidance of the teacher, to infer the target idea. Figure 6.15 suggests phases of understanding and a probable sequencing that, based on these video data, these students experienced. Students often begin with common alternative conceptions, such as the "clashing currents" model. Students then infer, separately, that the bulb must be connected at the bottom and side and that the positive and negative ends of the same battery must be connected into the circuit, as shown in Section B of Figure 6.15. Students then may infer that each component of an electrical circuit must be connected into the circuit at both ends, which is physically the same as the idea that they must form a loop, for electricity to flow (shown in Section C). Finally, some number of instances of this phenomenon may be observed before students infer that this circuit principle is generally applicable, as shown in Section D of Figure 6.15.

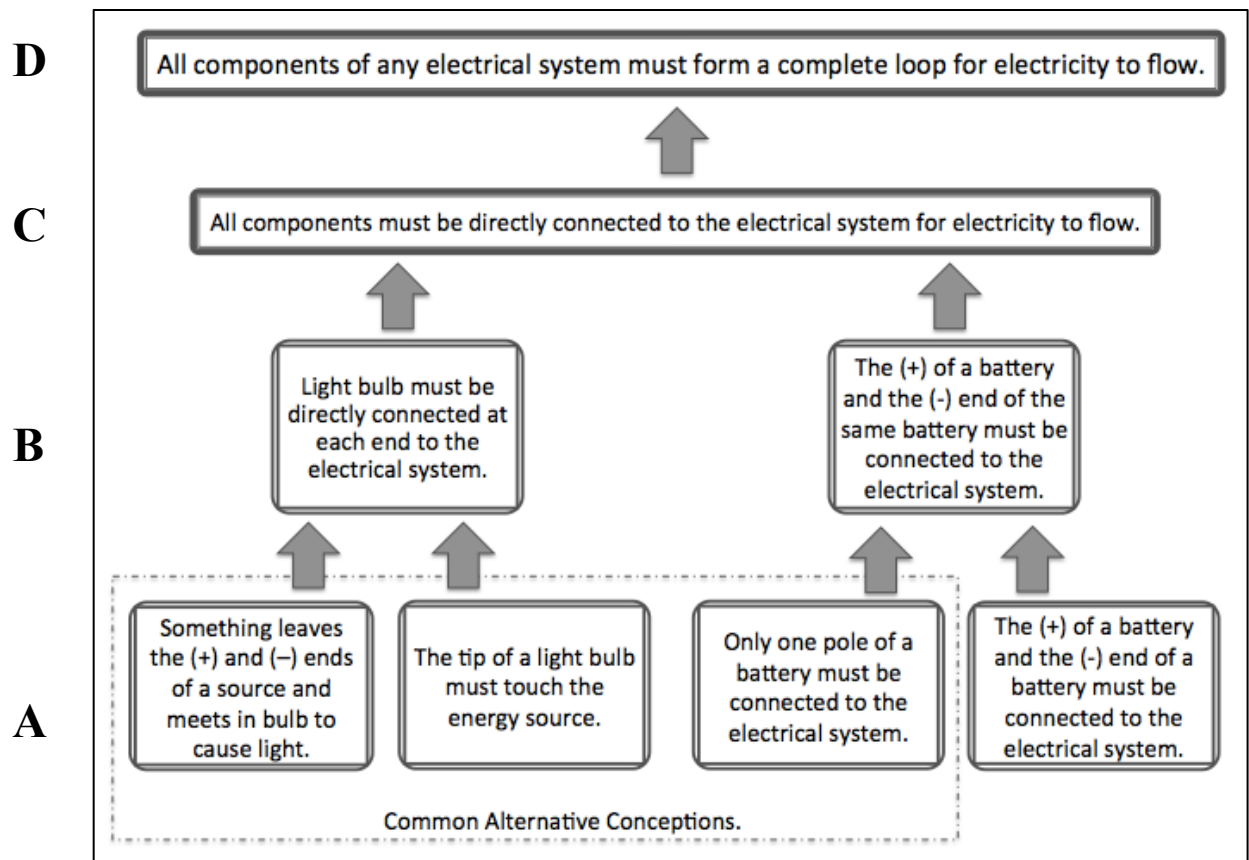
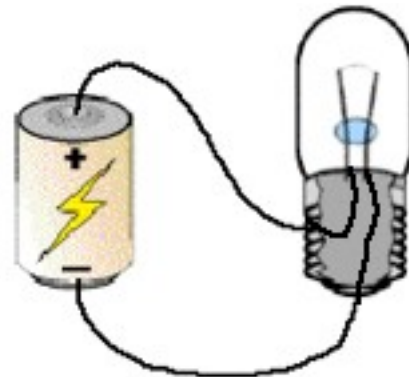


Figure 6.15. Evolving conceptions toward general circuit principle. (Shown previously)

The sequence in Figure 6.15 certainly does not represent the only way that a learner may arrive at this general principle. Rather, it is a plausible sequence that is consistent with the design of the curriculum and the video evidence analyzed here. One may argue that the process of scientific induction is not complete until the explanation has undergone the consensus-building process. In the PET classroom setting, this would mean that the class would need to reach consensus on the best explanation for the evidence available. I will not argue for one position or the other here. However, the consensus-building activity, the Summarizing Discussion, will be analyzed in the next section.

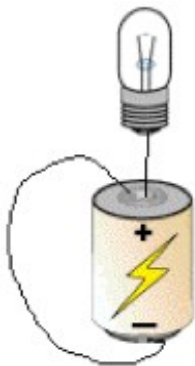
Summarizing Questions

S1. Draw a continuous line that shows the pathway of conductors from one end of the battery, through the bulb, to the other end of the battery. As you did in Step 3 of Experiment #3, be able to describe in words the different parts of the pathway.



Starting at the positive end of the battery, there is a wire connecting the positive end to the side of the bulb. Inside the bulb, one filament support wire connects the side of the bulb to one end of the filament. Another filament support wire connects the other end of the filament to the bottom tip of the bulb. Finally, a wire connects the bottom tip of the bulb to the negative end of the battery.

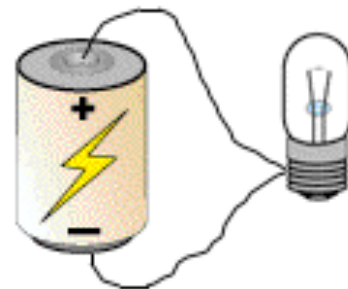
S2. The pictures below represent three different ways of putting together a battery bulb and one or more wires. In each case indicate whether the bulb will light or not light. Justify your choice in terms of the ideas developed in this activity (i.e. the conditions necessary to light a bulb).



(a) ne wire touches the positive end of the battery and the tip of the bulb. A second wire touches the positive end of the battery (not the knob in the middle) and the negative end of the battery.



(b) One wire touches the negative end of the battery and the metal side of the bulb. A second wire touches the positive end of the battery and the tip of the bulb.



(c) One wire touches the positive end of the battery and the metal side of the bulb. The other wire touches the negative end of the battery and the metal side of the bulb.

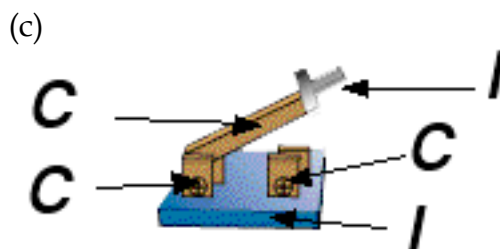
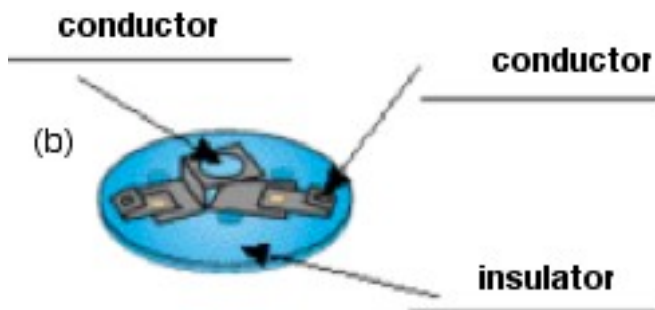
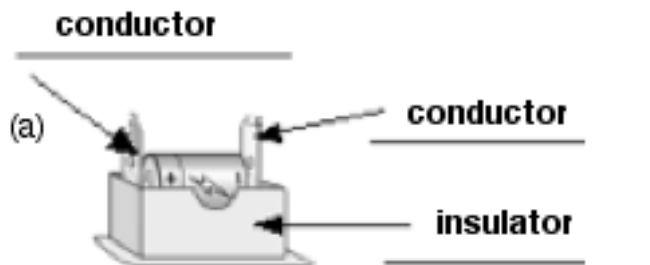
(a) The bulb will not light because both side of the bulb are not connected in the circuit

to both sides of the battery.

(b) The bulb will light because one side of the battery is connected to one side of the bulb, and the other side of the battery is connected to the other side of the bulb.

(c) The bulb will not light because both sides of the bulb are not connected in the circuit to both sides of the battery.

S3. Below are pictures of a battery holder, bulb holder and switch. Several parts of these components are identified. Indicate whether you think each part is a **conductor** or an **insulator**. Justify your answers.

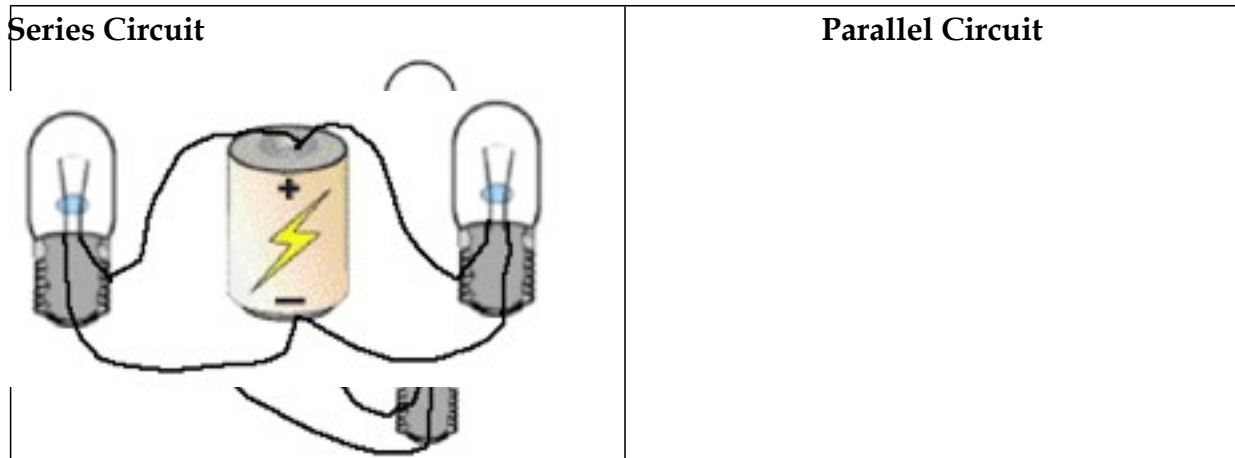


S4. In Experiment #4 you constructed two different circuits, each with a battery and two bulbs. Assume that each bulb is in a bulb socket.

Redraw the two circuits below, but make the bulb and socket large enough in each

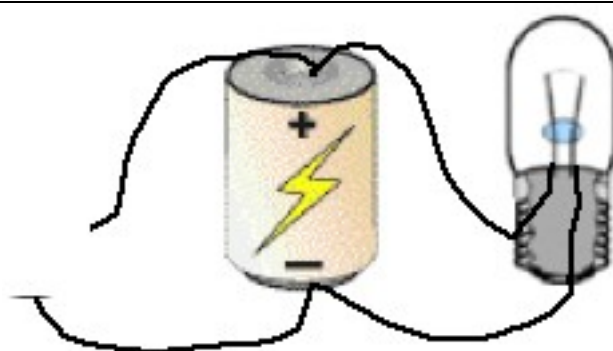
case to explicitly show the different parts of the socket and the filament support wires and filament in each bulb. Using a different color pen or pencil, trace a conducting path (or paths) from each end of the battery, to each socket, through the inside of each bulb, and then to the other end of the battery.

[Note: To make the pathways easier to see, the bulb sockets have been left out of the pictures of the two circuits below. One clip on the bulb holder connects directly to the bottom tip of the bulb, and the other clip connects directly to the screwy side of the bulb.]

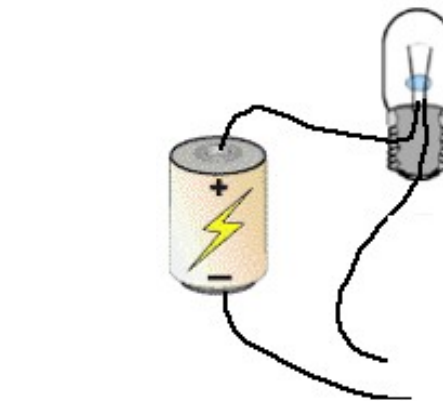


S5. Consider the same two circuits you drew above. **Write a scientific explanation for why (a) in one case, when a bulb is unscrewed from its socket, the other bulb remains lit. (b) Also explain why in the other case, when a bulb is unscrewed from its socket, the other bulb goes out.** For each case, your explanation should include a diagram of the circuit with one bulb unscrewed from its socket, and a written narrative for why the other bulb either continues to be lit or goes out. Your diagrams should be large, like the ones you drew in S4.

(a) If you remove the left bulb in the parallel circuit, the bulb on the right is still part of a complete circuit—there is a continuous conducting pathway from one end of the battery, through the right bulb, to the other end of the battery. Therefore, the bulb on the right still glows.



(b) If you remove the bottom bulb in the series circuit, however, there is no longer a continuous conducting path from one end of the battery through the bulb, to the other end of the battery. Therefore, the remaining bulb will not light.



Participate in a whole class discussion about answers to the above questions.



CHAPTER 5

Scientists' Ideas

ELECTRIC CIRCUIT INTERACTIONS

By the 18th century experiments with electricity were the rage and scientists such as Stephen Gray and Charles Dufay began to notice the effect of connecting electrical materials together using a wire or a thread.

A vital experimental finding in the history of the electric circuit interaction was discovered largely by accident by Luigi Galvani who produced an electrical convulsion in a frog's leg. This accidental discovery led Alessandro Volta to construct the first "voltaic cells" or batteries in the early 19th century. Experiments with this device led to the discovery that a noticeable quantity of heat was generated in the wire connecting the battery. This discovery was astonishing from the standpoint of energy because no external energy was being supplied to the battery. Therefore, scientists had to generate an understanding of energy transformations in order to explain the source of this heat.

Some scientists' current ideas about the electric circuit interaction are listed below. Read through these ideas with your team and, below each idea, make a note of the evidence or examples you have seen in your investigations that support each idea.

Idea EC1 - An electric circuit interaction occurs when a source of electrical energy is connected in a closed path of conductors to an energy receiver:

If the path is opened, or if a non-conductor (insulator) is placed in the direct path, then the electric circuit interaction will cease occurring.

Evidence/example:

- (a) Examples of energy sources for electric circuits: battery, generator, and solar cell.
- (b) Examples of energy receivers for electric circuits: light bulb, motor, and buzzer. In the electric circuit descriptions that follow we will assume the battery is the energy source in the circuit. However, the ideas still hold for any other type of energy source.

Idea EC2 - Each device in an electric circuit is two-ended; and each end must be directly connected in the circuit

(If only one end of a device is connected in the circuit, then the device or circuit will not work.)

Evidence/example:

Idea EC3: Electric circuit interactions can be described in terms of *electrical energy*, and the law of energy conservation applies to all devices in the electric circuit

During an electric circuit interaction, electrical energy is transferred from the energy source to the energy receiver. No energy is “used up” or “destroyed.” Instead, each device in the circuit transforms one type of energy into one or more other types. It is convenient to draw input/output energy diagrams to describe the interactions between the device and other objects. In all cases, the law of conservation of energy applies to the energy description.

Evidence/example:

Idea EC4: All electric circuit devices warm up when operating and transfer heat energy to the surroundings. (In fact, in any type of interaction where something is moving, or some part of a device is moving, there is always friction present and consequently the device will warm up and transfer heat energy to the surroundings.)

Evidence/example:

Idea EC5: The efficiency of an electrical device is a measure of how efficient the device is in transforming its input energy into useful energy output. (For a battery, the decrease in chemical potential energy is used instead of input energy.)

$$\text{Efficiency (in \%)} = \frac{\text{Useful Energy Output}}{\text{Energy Input}} \times 100$$

Evidence/example:

Idea EC6: An important variable in electric circuits is the rate at which electrical energy is transferred from the energy source to one or more energy devices. By definition, the rate of energy transfer is the amount of energy transferred from the source to the device in one second. The unit is a joule/sec or watt.

Evidence/example:

Idea EC7: The brightness of a bulb depends on the rate of electrical energy transferred to it: the higher the rate, the brighter the bulb.

Evidence/example:

Idea EC8: Electric circuit interactions can be described in terms of *electric current*, which is the amount of electric charge moving past any point in the circuit in one second.

Electric current is measured in units of amperes (A) or milli-amperes (mA) using a device called an ammeter. The electric charges flow in one direction around the circuit: out of one end of the battery, through the devices, and back into the other end of the battery.

Evidence/examples:

Idea EC9: The value of the electric current in a circuit depends both on the value of the battery voltage and the value of the resistance in the circuit. The relationship between these quantities is given by Ohm's Law:

$$V = I/R$$

where battery voltage is measured in volts and resistance is measured in ohms.

Evidence/examples:

Idea EC10: The resistance of the filament is a measure of how much of an obstacle the bulb filament is to the flow of electric charges through it. The amount of resistance of a bulb filament depends on the length, thickness, temperature and type of material of the filament:

Longer filaments offer more resistance than shorter filaments. Thicker filaments offer less resistance than thinner filaments. As the temperature of the filament increases, its resistance also increases. Some metals, like nichrome, have a much greater resistance than other metals, like copper, for the same length, thickness and temperature.

Evidence/examples

Idea EC11: Electric current does not change in value around a single loop in a circuit:

As the electric charges move through the circuit, *none* of them disappear (or are lost) and *no* new charges are created. The charges just keep circulating around the loop like cars at a racetrack. The electric current has the same value at each position within a single loop.

Evidence/examples:

Idea EC12: Electrical devices can be connected to a battery either in series or in parallel:

- (a) In a *series* circuit, all devices are connected in a single loop with the battery. The greater the number of devices, the lower the value of the electric current.

Evidence/examples:

- (b) In a *parallel* circuit, each device is connected in its own separate branch or pathway to the same battery. The greater the number of devices, the greater the value of the electric current.

Evidence/examples

Idea EC13 - A *short circuit* is a special situation that happens when a wire with low resistance (e.g. copper) directly connects the positive and negative terminals on a battery (without a bulb in the same pathway).

During a short circuit the battery can get very warm because the rate of increase in thermal energy is very high. Also, the rate of decrease in chemical potential energy is very large, and this means the battery can “die” much sooner than it would in a circuit that is not shorted. In the shorting wire, because it has a very low resistance, the value of the electric current can be very high. In a household circuit, to prevent a large increase in current if there is a short, a fuse or circuit breaker will open up causing the circuit to stop functioning.

Evidence/examples: