Comparing Open and Guided Inquiry Activities in an Informal Physics Program To Promote Agency, Communication, and Reasoning

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ABSTRACT

In this thesis, we investigate an informal after-school science program. We examine two inquiry curricula used in this program; one more guided and the other more open. We have developed new methods to analyze middle school children's scientific notebooks, and we measure how the children exhibit agency, how the children communicate, and the mechanistic reasoning children use. We compare the two curricula and find that the children exhibit more agency in the open curriculum, write and draw more in the open curriculum, demonstrate a wide variety of scientific communication, and use more varied types of mechanistic reasoning in the open curriculum. These aspects can be linked to science identity, and we conclude that the more open curriculum supports the development of positive science identity.

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CHAPTER I

INTRODUCTION

1.1 Background: Challenges in STEM Education

According to the National Research Council report, "Rising Above the Gathering Storm" the future prosperity of the United States' economy relies on fostering a population that is educated in science, math, and engineering [1]. However, the United States scores lower than average among other countries in science, technology, engineering and mathematics (STEM) performance. According to the results from the 2013 Program for Internal Student Assessment (PISA) test, a worldwide assessment of 15 year olds in 34 industrialized countries, the U.S. placed 21st in science, and 26th in mathematics [2]. In 2009, only 4% of bachelor's degrees awarded in the United States were awarded for engineering programs, 5% for biological sciences, 3% for mathematics, and 1% for physical science [3]. As a whole, only 13.7% of college degrees and certificates awarded in the United States were in STEM fields in 2011 [4]. The percent of degrees and certificates awarded in STEM fields in Colorado is only slightly better at 14.9% [4].

While U.S. students are falling behind other countries in performance measures of STEM education, U.S. ethnic minority students are falling behind their white counterparts. According to the results of the 2005 NAEP science exam [5], Latino students scored about 10% lower than Caucasian students in grades 4, 8, and 12, while African-American students scored 1%-2% lower than Latino students. In Colorado, 55% of Caucasian 8th graders are at or above proficient in science [5], while only 26% of African American and 18% of Latino 8th graders are at or above proficient in science. Ethnic minorities are grossly underrepresented in STEM education across the country. In 2009 the U. S. Census Bureau detailed in a press release that Hispanic Americans currently make up 15% of the total U. S. resident population, making Latinos the largest minority group in America [6]. In this same press release, it was stated that the growth rate for Latinos in the U.S. was 3.2%, over three times larger than the total U.S. population growth rate. However, in 2009 Latinos only made up 8% of engineering bachelor's degrees awarded, 7% of biological sciences bachelor's degrees, 7% of mathematics degrees, and 7% of physical science degrees [3]. African Americans earned 4% of engineering degrees, 7% of biological sciences degrees, 9% of mathematics degrees, and 6% of physical science degrees [3]. Caucasians, on the other hand, made up 65% of all engineering degrees, 60% of biological science degrees, 62% of all mathematics degrees, and 65% of all physical science degrees. In Colorado, Latinos are 26.6% of the college-age population, but only receive 7.4% of STEM degrees [4]. African Americans make up 4.3% of the college-age population in Colorado and receive 3.5% of STEM degrees.

Women are also underrepresented in STEM education. In 2009 women accounted for 18% of engineering bachelor's degrees and 25% of mathematics degrees [3]. Women were actually more represented than men in the biological sciences degrees earning 60% of the bachelor's degrees awarded and women were more fairly represented in physical science earning 42% of physical science degrees, however, within the physical sciences women earn 50% of chemistry degrees and only 19% of physics degrees [3]. Thus, women are underrepresented in engineering, mathematics, and physics. In Colorado, women earn only 33.5% of degrees awarded in STEM fields [4].

In order to compete in the global economy, the National Research Council calls for one million more STEM majors in this decade [7]. However, our higher education system is not producing enough STEM graduates to meet this demand. Furthermore, ethnic minorities and women are underrepresented in STEM education. Our educational system needs to attract more people to STEM fields, especially ethnic minorities and women.

1.2 The Potential for Informal Science

One way to attract more people to STEM degrees is through informal science education. According to the National Research Council's publication entitled "Learning Science in Informal Environments" [8], structured informal science environments have the potential to promote science interests, positively influence academic achievement in the sciences, and may expand learners' ideas about scientific career options [8]. Children are presented with abundant opportunities to learn about science in non-school settings. In the United States, the state requiring the most hours spent in formal school, Texas, requires middle school children to spend 1260 hours in school per year [9]. Thus, in the U.S., at most 14% of a middle school student's year is spent in school, leaving the majority of a student's time for pursuits outside of school. Informal science education is any educational experience that happens outside of formal schooling and includes a wide array of settings such as, libraries, museums, zoos, community centers, nature centers, afterschool clubs, and even includes everyday activities like gardening and hiking [8]. Structured informal science education programs may happen in schools, community center spaces, and science organizations [8].

Within these informal settings, many different types of science learning may occur. One common theme throughout these informal learning environments is the National Research Council's six strands of learning science that are particularly prevalent in informal environments [8]. These strands describe goals and outcomes for students in these learning settings:

> *Strand 1: Experience excitement, interest, and motivation to learn about phenomena in the natural and physical world.*

Strand 2: Come to generate, understand, remember, and use concepts, explanations, arguments, models, and facts related to science.

Strand 3: Manipulate, test, explore, predict, question, observe, and make sense of the natural and physical world.

Strand 4: Reflect on science as a way of knowing: on processes, concepts, and institutions of science; and on their own process of learning about phenomena.

Strand 5: Participate in scientific activities and learning practices with others, using scientific language and tools.

Strand 6: Think of themselves as science learners and develop an identity as someone who knows about, uses, and sometimes contributes to science.

Strands two through five should be present in informal settings as well as formal school-based learning. Strands one and six, however, may appear less in formal school curricula; however, informal environments are well suited to encourage students in these strands [8]. The focus of strands one and six, *developing excitement, interest and motivation to learn about science* and *development of an identity as someone who knows about and can do science* have been linked to career paths in science [10]. Thus, through encouraging strands one and six, informal environments have the potential to encourage learners to pursue careers in science.

1.3 Our Study

For certain designed informal environments, such as afterschool and museum programs, there are many different types of curricula that may be implemented. Our study will focus on inquiry curricula, a type of hands-on, student-driven way of learning that gives priority to evidence-based explanations [11]. We will discuss inquiry in more detail in Chapter 2. There is a wide spectrum of inquiry styles ranging from more guided, where the teacher and activities provide more structure, to open, where the learner directs structure [11]. Our study compares guided and more open inquiry activities in an informal learning environment. In Chapter 3, we discuss the setting of this study and previous studies, and in Chapter 4, we discuss the two curricula used. We compare three curricular emphases associated with inquiry between the two curricula. In Chapter 6, we identify how students are ***exercising agency*** within the curricula, in Chapter 7, we examine how students ***communicate*** about science, and in Chapter 8, we analyze the ***mechanistic reasoning*** used in student communication. We analyze our results in light of promoting strand six (*scientific identity development*) of informal learning environments.

CHAPTER II

DEFINITIONS OF INQUIRY

In this thesis we compare two curricula that take different approaches to promoting inquiry. It is important to get a clear definition of what inquiry is, in order to understand the two curricula. To define inquiry, we look historically, to John Dewey, a philosopher in the early 20th century [12]. Dewey was one of many people who paved the way for inquiry in education with his theories and ideas on reflective thought [12]. Dewey specifically mentions the need for reflective thought in education in his 1910 publication of "How We Think" [13]. In modern times, the National Research Council's publication of "Inquiry in the National Education Standards," [11] has had much impact on educational policy. We look to Dewey's reflective thought, the NRC's definition of inquiry, and other modern definitions of inquiry to inform this thesis.

2.1 John Dewey's Ideas on Reflective Thought

Reflective thought is defined by Dewey as "active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it, and the further conclusions to which it tends." [13]. Reflective thought involves a five-step process. This process begins with "a felt difficulty." This situation could be a problem that needs to be solved, or a discrepant event or phenomena. The next steps are to identify what is known about the difficulty, and suggest a possible solution or explanation. The students use reasoning to analyze the solution or explanation. The final step is to make observations and experiments in order to accept or reject the solution or explanation. Observation is at the beginning and end of this process [13]: one must first observe the nature of the initial problem, and at the end of the process observations allow for the acceptance or rejection of the solution or explanation. At the essence of this process of reflective thought is the idea that belief or judgment is suspended or postponed until observations are made and evidence is gathered to support the belief or judgment [13]. These steps for reflective thought are operations in one approach to inquiry.

Dewey paves the way for the modern framing of inquiry in education when he argues that students in schools should engage in reflective thought instead of, what he considered to be commonly taught in schools, “sheer imitation, dictation of steps to be taken, mechanical drill” [13]. Dewey argues that such practices are used in schools because they obtain the fast results of students memorizing science facts. This outcome, however, is not at the core of learning science. Often, teachers engage students by having boisterous personalities and personal strong points but overlook engaging students by the value of the subject for its own sake [13]. This situation leads to students relying on the teacher as the source of authority – for instance, they may ask questions of the teacher to discover what the teacher wants them to say. This approach is in direct opposition to reflective thought in the classroom where students would ask questions such as “does this satisfy the inherent conditions of the problem?” [13]. Reflective thought in the classroom is student-centered instead of teacher-centered. Dewey states that, “one might well say he has sold when no one has bought, as to say he has taught when no one has learned. And in the educational transaction, the initiative lies with the learner even more than in commerce it lies with the buyer” [13]. Dewey argues that best practices in schools rest on the assumption that observation is an active process wherein the students must be actively making observations and collecting evidence to discover something or solve a problem.

In light of Dewey’s framing of reflective thought, some hallmarks of an inquiry learning environment can be found. First, there must be some sort of problem, question, or discrepant event that engages the student. According to Pugh, this beginning is an idea that “foreshadows future happenings” and is “personally worthwhile” to the student [14]. Because the idea is personally worthwhile, it stimulates anticipation and drives a desire to try out the idea [14]. Thus, the student makes an explanation to potentially solve the problem or answer the question and makes observations and collects evidence to test ideas. Personally worthwhile ideas can result in a transformation of our experience in the world, allowing us to interact with the world in new ways. Pugh refers to this process as a “transformative experience” [14]. Dewey also stresses that in reflective thought it is important that evidence must be collected and analyzed before coming to a conclusion. Finally, this process is student-centered. The teacher is not telling the student an answer to memorize, rather, the student must be actively observing and collecting evidence to support or refute their claims. This approach lays the groundwork for the modern sense of inquiry.

2.2 The National Research Council Defines Inquiry

The National Research Council (NRC) defines inquiry as “the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world” [11]. It is important for students to engage in the same practices as scientists. The NRC also defines five essential features of classroom inquiry [11]. Learners are first engaged by scientific questions, learners give priority to evidence, learners use evidence to develop and evaluate explanations that address questions, learners evaluate their explanations with previous scientific knowledge, and learners communicate and justify their proposed explanations. Similarly to Dewey’s reflective thought, the NRC’s essential features of inquiry involve finding a question that must be answered or a problem that must be solved, and using evidence that is collected in order to support or refute claims. The NRC, however, also includes the social aspects of inquiry, where the learner must consider other ideas and communicate and justify their findings.

The National Research Council's definition of inquiry is one that highly impacts current educational policy in that is has informed the Next Generation Science Standards (NGSS) [15]. The NGSS are a set of standards, released in 2013, for our nations' schools to follow in science education in order to make sure our nation's students are career and college ready [15]. Twenty-six states were involved in designing the standards and over forty states have expressed an interest in adopting the standards in the future [16]. The NGSS calls for students to engage in scientific practices, or the behaviors that various different scientists engage in when conducting research [15]. The standards refer to the National Research Council's definition of *inquiry* but the NGSS do not call these practices *inquiry*. There are many definitions of the word inquiry that can differ significantly, and the NGSS does not use the word in order to avoid misconceptions in the definitions of inquiry. While we acknowledge some controversy surrounding the word, we will still be using the word inquiry in our study.

2.3 Guided and Open Inquiry

Another addition that the NRC adds to our growing definition of inquiry is the idea that within inquiry a teacher may vary the level of detailed guidance she provides students [11]. The level of guidance provided can range from guided inquiry to open inquiry, where very little guidance is given. Joseph Schwab, a professor of natural sciences and education in the 20th century, outlined three types of inquiry that could be used in the science classroom [11]. In guided inquiry, “laboratory manuals or textbook materials could be used to pose questions and describe methods to investigate the questions, thus allowing students to discover relationships they do not already know.” In the middle of the spectrum, “instructional materials could be used to pose questions, but the methods and answers could be left open for students to determine on their own.” Finally, “in the most open approach, students could confront phenomena without textbook- or laboratory-based questions. Students could ask questions, gather evidence, and propose scientific explanations based on their own investigations.” The NRC breaks down this spectrum for each essential feature of classroom inquiry in Table 1.

Table 1. National Research Council’s Essential Features and Level of Guidance in Inquiry [11].

Essential Feature	More open inquiry <--------------------------------------> More guided Inquiry			
1. Learner engages in scientifically oriented questions	*Learner poses a question*	*Learner selects among questions, poses new questions*	*Learner sharpens or clarifies question provided by teacher, materials, or other source*	*Learner engages in question provided by teacher, materials, or other source*
2. Learner gives priority to ***evidence*** *in responding to questions*	*Learner determines what constitutes evidence and collects it*	*Learner directed to collect certain data*	*Learner given data and asked to analyze*	*Learner given data and told how to analyze*
3. Learner formulates ***explanations*** *from evidence*	*Learner formulates explanation after summarizing evidence*	*Learner guided in process of formulating explanations from evidence*	*Learner given possible ways to use evidence to formulate explanation*	*Learner provided with evidence and how to use evidence to formulate explanation*
4. Learner connects explanations to scientific knowledge	*Learner independently examines other resources*	*Learner directed toward areas and sources of scientific knowledge*	*Learner given possible connections*	*Learner told what connections are*

5. Learner communicates and justifies explanations	*Learner forms reasonable and logical argument to communicate explanations*	*Learner coached in development of communication*	*Learner provided broad guidelines to use sharpen communication*	*Learner given steps and procedures for communication*

2.4 Other Definitions of Inquiry

While the NRC has a very specific definition of inquiry, there are many other approaches to the term inquiry. A team of teachers and education researchers at the University of Colorado define inquiry as, "socially constructing evidence-based meaning of phenomena through intentionally sequenced processes" [17]. Unpacking this sentence reiterates some points from the previous sources. Inquiry involves making meaning of phenomena, or addressing some sort of scientific question or problem. Inquiry must involve collecting evidence and explanations must be evidence based. The process must be intentionally sequenced, both Dewey and the NRC put forward steps, such as, pose a question, collect evidence, make an evidence based explanation. Finally, this process is social, ideas and explanations must be shared and discussed.

The Exploratorium's Institute for Inquiry also offers a definition of inquiry. "Inquiry is an approach to learning that involves a process of exploring the natural or material world and that leads to asking questions, making discoveries, and testing those discoveries in the search for new understanding" [18]. According to the Institute, inquiry is a process beginning with the learner posing a question or making an intriguing observation. The learner then makes observations, collects data and evidence, and draws on the insights of others and of written literature to consider the initial question. The Institute also points out that this is not a linear process but a "back and forth or cyclical" process [18]. Finally the learner takes observations and evidence and makes meaning out of the experience. This entire process involves conversations with others, comparing of evidence and interpretation with others, reflection, and interpretation of collected evidence.

2.5 Common Characteristics of Inquiry for This Study

From the definitions of inquiry discussed above, it is clear that inquiry activities have some common characteristics that will be used in this study. The learner is first engaged by some scientific question or problem. The learner actively makes observations and collects evidence. The learner will use evidence and reasoning to make explanations to answer questions. The learner must finally communicate their explanations. There is also a broad spectrum of what is considered an inquiry activity. Heavily guided inquiry is characterized by more direction of activity from the materials and a teacher, while more open inquiry is more directed by the learner.

2.6 Implementations of Inquiry in Our Community

Inquiry can be implemented in many different settings. While there is a call for inquiry in school settings [11], informal environments often use and benefit from inquiry activities. Here in Boulder, we have many informal science programs that incorporate inquiry practices. Science Discovery [19] is a summer camp for K-12 children featuring hands-on science learning located on the University of Colorado Boulder campus and areas surrounding Boulder. The CU Wizards program is a monthly science show that engages children with fascinating demos presented by renowned CU professors [20]. El Pueblo Magico is an afterschool program in Sanchez Elementary School run by CU faculty and students that focuses on new media and technological design and scientific knowledge especially health sciences and energy [21]. Partnerships for Informal Science Education in the Community (PISEC) [22] is an informal afterschool physics program for K-8 children located in many schools around Boulder and in some community centers in housing projects. We have just highlighted a few of the many informal science programs offered in Boulder that use inquiry practices. This thesis will focus on inquiry curricula in the Partnerships for Informal Science Education in the Community program.

CHAPTER III

STUDY SETTING

In Chapter 1, the potential for informal science in promoting enthusiasm for science and positive science identity was discussed. In this chapter, we will discuss the setting of this study, a program named Partnerships for Informal Science Education in the Community, or PISEC.

3.1 Partnerships for Informal Science Education in the Community (PISEC)

The JILA Physics Frontier Center Partnerships for Informal Science Education in the Community (PISEC) program provides opportunities for university students such as undergraduates, graduate students, and post docs, to teach inquiry-based science activities to K-12 children [22]. The children who attend PISEC generally range from 5th through 8th grade, although the age range is sometimes younger at certain locations. The university students, known as university educators (UEs) meet the children once per week at a community center or school to engage in hands-on inquiry science activities together. The program generally runs for 8-9 sessions over the course of one semester. About 3-4 children work with one UE each week. Sometimes a group of children will keep working with the same UE for the duration of the semester; however, often the groups are mixed up with different children working together and working with different UEs each week. The children document their work in a scientific notebook each week. During the final weeks of a session at the site, children make a Stop Action Motion (SAM) [23] movie about what they learned. At the end of each semester, the children take a field trip to the University of Colorado Boulder campus. The children tour physics laboratories, see their SAM movies on a big screen, get awards and prizes, and participate in a fun physics demo show including liquid nitrogen ice cream.

3.2 5th Dimension Model

The PISEC program is modeled after the 5th Dimension (5D), an afterschool literacy program in California [24]. 5D is a model where a college or university, with interests in researching community institutions for children, conducts and researches activities in partnership with local community institutions. Through the joint creation of an afterschool space for children's programming, a university-community link is formed in which both parties benefit [25]. This hybrid space is embedded in many levels of context, depicted in Figure 1. At the inner level are the interactions between children, people from the university, and tasks, which for the initial 5D programs were generally computer games. These interactions happen within the context of the 5th Dimension system, which is located in a larger institution such as a school or a youth club. The entire program occurs as a part of the community in which the program is located [25].

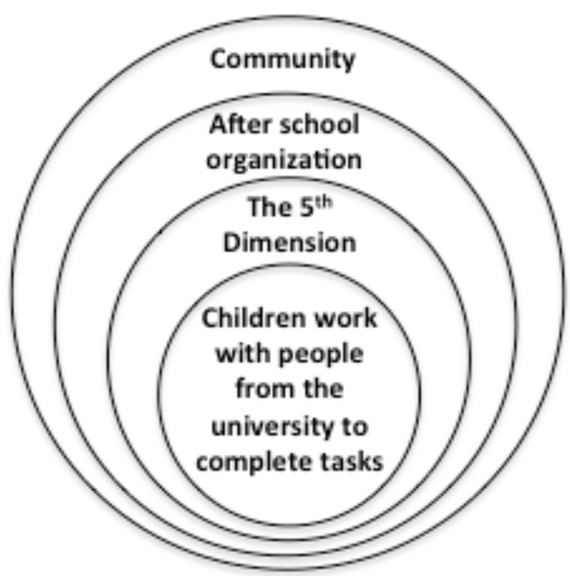


Figure 1: 5th Dimension contexts. Concentric circles depict the many levels of context in the 5th Dimension afterschool program [25].

Following the 5D model, PISEC establishes partnerships between the University of Colorado Boulder and community organizations around Boulder to build a space for an informal science program within a community (depicted in Figure 2), thus reaching children where they live and spend time outside of school [26]. As in the 5th Dimension, children work with people from the university to interact with artifacts, such as science activities, hands-on experiments, and simulations within the PISEC afterschool program. The program is set within youth serving institutions such as schools and community centers, which are a part of the community in which they are located.

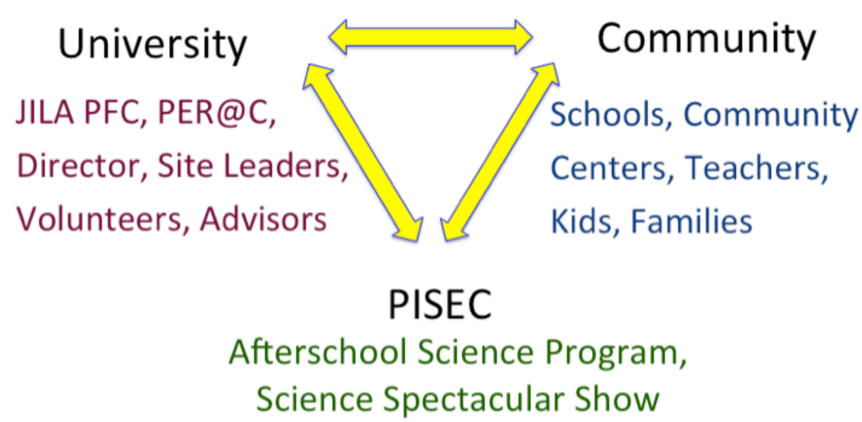


Figure 2: PISEC partnership model. The University of Colorado Boulder and local community organizations partner to create a space for the PISEC program.

The PISEC program shares the same core values and principals as the 5th Dimension that guide the theoretical framework of the program [25]: Motivation for participation in the program is important, and learning should be situated in everyday cultural activities, especially play for children. Collaboration must occur between children and adults in which the roles of teacher and of the learner can change and are shared. Participants in this collaboration are diverse in age, educational experience, gender, culture, language, and socioeconomic status. Participants are encouraged to formulate personal goals through choices, such as, the decision to participate, what activities to do, and what level of expertise to attempt. The system promotes the use of a wide range of communication practices and the use of artifacts to promote the achievement of personal goals. Finally, participants are encouraged to expand on activities and reflect on and communicate about their problem solving efforts.

3.3 PISEC Locations

PISEC partners with several different community organizations. The Mathematics Engineering Science Achievement program [27] works with PISEC in middle school sites to recruit children to participate. MESA selectively recruits children from low-income families, ethnic minorities, girls, and children who are first generation in their family to attend a university [27]. Any child interested in joining MESA may join; however, teachers or counselors at school seek out and invite children that fit the target demographic. Teachers especially look for children who may have trouble learning in a regular classroom and could potentially succeed in an informal setting. Also many children hear about the MESA program from their friends and request to apply. In elementary school sites, PISEC partners with Family Resource Schools, a joint program between Boulder Valley School District and Boulder County, providing low cost after school resources to schools identified as having a large population of high risk students [28].

PISEC also partners with other community organizations including CLACE (Latin American Center for Arts, Sciences, and Education), a program dedicated to encouraging Hispanic American youth in the arts and sciences [29]. PISEC holds programs in the community centers of local housing projects, partnering with Boulder Housing Partners [30], and Casa de la Esperanza, a community comprised of migrant agricultural workers [31]. This thesis will only use data from two middle schools that partnered with the MESA program. We will describe these schools in more detail in Chapter 5.

3.4 The PISEC Game System

One of the theoretical principles that PISEC and the 5th Dimension are built upon is the idea that learning should be situated in everyday cultural activities such as play. The inspiration for incorporating play in learning within these programs has roots in Lev Vygotsky's theories regarding the importance of play in childhood development [32]. Play can help children learn the social norms of their community, and through play children are able to act out and fulfill desires that may not be obtainable at the time [32]. In PISEC, children participate in scientific practices through play, thus learning social norms of science, and also giving children the opportunity be part of a scientific community, and practice an identity as scientists.

In the original 5th Dimension program, the children interact with the program activities through a game board that has a maze structure [25]. Children follow the path of the maze to reach different activities, and this structure helps incorporate play in the environment. In the spring of 2010, PISEC first began using a fantasy story line along with the usual science content. The story is that a mythical figure known as the Wizard transports the children to a mythical cave system in France. Upon teleportation to the caves, the entrance collapses leaving the children "stuck." The children must figure out how to light a light bulb in order to explore the cave system and find a way out. The caves provide an imaginary space in which the children can interact with science. Each section of the curriculum is set in a different numbered cave, ranging from Cave 1 to Cave 5. Each cave system also offers an optional challenge section where children can complete more experiments similar to the ones in the caves. Each cave system also has logic puzzles that the children can choose to complete. The cave system is scaffolded so that Cave 1 has more basic scientific ideas while Cave 5 builds on knowledge obtained in previous caves and contains more advanced topics. Children must complete the caves in order, and may not advance past Cave 2 without completing at least one challenge.

The caves story line was used for a circuits curriculum; a similar maze story line was used with a mechanics curriculum. The circuits curriculum with the caves story line was implemented several semesters, including during Fall 2011. In Spring 2012, the caves and mazes story line was replaced by a more simple story line of investigating a laboratory. The more simple story line was used in order to promote learner agency in the program as it did not force children to complete activities in a specific order like the original story line. In Chapter 6, we will discuss how this change influenced learner agency in more detail. A game board was also added where children can move their characters, small paper dolls with their pictures, to four different rooms each with a different theme of physics experiments (shown in Figure 3). Each room in the laboratory has three levels. The levels are scaffolded so that more novice activities can be done at Level 1, while more expert activities can be done at Level 2 or Level 3.

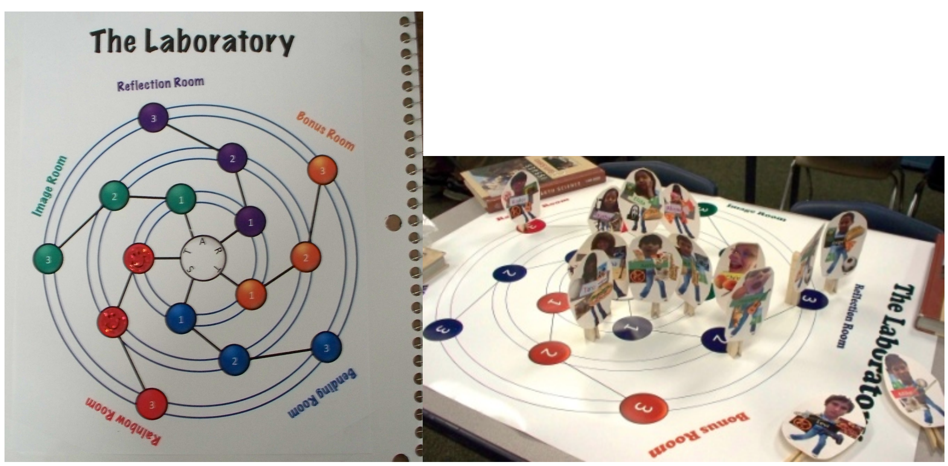


Figure 3: Picture of game boards. A game board in a notebook (left) and a picture of large game board with children's paper dolls (right) indicating where they are in the "laboratory".

3.5 Previous Research About Children in PISEC

Research is a large part of the PISEC program, and studies have been done prior to this thesis focusing on both children and adults participating in the program. The studies focused on children's content gains over the course of one semester and also children's attitudes and interest in science over the course of one semester.

In 2009, the children's work in the circuits curriculum was analyzed for content gains [33]. Children were given a pre and post test at the beginning and at the end of one semester of participation in PISEC. The study focused on 12 matched pre and post test scores. The test administered was the Conceptual Survey of Circuits (CSC), a short test asking students to draw a working circuit given a light bulb battery and wire. The CSC is scored on a six-point scale. Children received one point for any of the following characteristics: A drawing that included a battery bulb and wire, components drawn in a closed loop, the bottom and side of the light bulb were touched by wire or battery, indicating that both the bottom and side of a light bulb are connectors, the use of only one wire instead of two, and the drawing a configuration that would actually light. For example, with this scale children would receive only two points if they drew a picture like the third configuration in Figure 1 because the configuration includes all of the parts and is drawn in a closed loop but does not touch the bulb on both the side and bottom, and also does not light. The second configuration in Figure 1 would receive 5 points since it meets all requirements except having only one wire instead of two. The fourth configuration in Figure 1 would be awarded full points. This study found a significant difference between pre and post test scores with all (n=12) except one child scoring a perfect sore on the post test [33].

Another study analyzed the attitudes of children participating in the PISEC program. A new instrument for measuring middle school children's attitudes, the Children's Attitude Survey

(CAS) was created during the very first semester of the PISEC program in the Fall of 2007 [34]. The CAS was modified from the Colorado Learning about Attitudes in Science Survey (CLASS), an instrument designed at the University of Colorado to measure shifts in attitudes of college students over the course of introductory college physics [35]. The CAS took seven questions from the CLASS and reworded them to be in language more familiar to an elementary or middle school student. In 2009 and 2010, the CAS was studied in order to determine the validity of the instrument. The validity of the CAS was informed by interviews with students in PISEC, and the CAS went through many variations until three questions were thought to be valid. This assessment, in various forms, was given pre and post over the course of 8 semesters in the PISEC program and for the entire eight semesters found, on average, positive attitudes about science and no significant shifts in children's attitudes over the course of one semester [34]. However, in the interviews conducted, many children in PISEC expressed feeling "bored" with the curriculum and also wanted more hands on experiments.

3.6 Motivation to Transform PISEC Structure

After receiving feedback about the PISEC program from interviews with children, teachers and university educators were asked about the program as well. Many participants reiterated the children's sentiment that the curriculum was getting repetitive, and that more hands-on experiments would be more fun for the children. Although content gains were measured with the guided inquiry curriculum, because of the repetitiveness of the content, the scope of the guided curriculum was far to short. Thus, the PISEC directors determined to change the curriculum to a less repetitive and more open inquiry format. This change was implemented in order to support strands one and six of informal learning environments, to encourage enthusiasm for science and foster science identity, while continuing to increase content knowledge and allowing the children to cover more concepts. Thus, a transformed curriculum was developed for Spring 2012. In Chapter 4 we will describe the two curricula.

CHAPTER IV

INQUIRY CURRICULA IN PISEC

The PISEC program has used two different pedagogical approaches in the curricula. In this chapter, we give an overview of these two curricula and compare the two styles of inquiry used in each. We draw on descriptions in Table 1 to present evidence that one curriculum is more guided than the other.

4.1 Guided Inquiry Curriculum

The guided inquiry curriculum used in the PISEC program was modified from the Physics and Everyday Thinking (PET) [36] curriculum. This curriculum is structured in a way that promotes students to make content discoveries for themselves by conducting hands-on activities with guiding instructions. PET was initially designed to teach elementary pre-service teachers how to teach inquiry science. Currently, the PET curriculum is being modified and studied for use as a middle school and high school curriculum [17]. The directors of PISEC (not the developers of PET), however, modified parts of the PET curriculum to be used by elementary and middle school students in the PISEC afterschool program. The modified PET curriculum was used in PISEC from Fall 2007 through Fall 2011. The PISEC directors modified the circuits, mechanics, and the magnets PET curricula [37]; this thesis focuses on the circuits curriculum because it was the last modified PET curriculum to be run in Fall 2011. Analyzing the circuits curriculum allows us to compare the same children's work who also participated in the program in Spring 2012 with the new curriculum.

You will need: One loose battery, one loose bulb, two bare copper wires, Playdoh.

Does the bulb light? Write **YES** or **NO** next to the word: **OBSERVATION**.

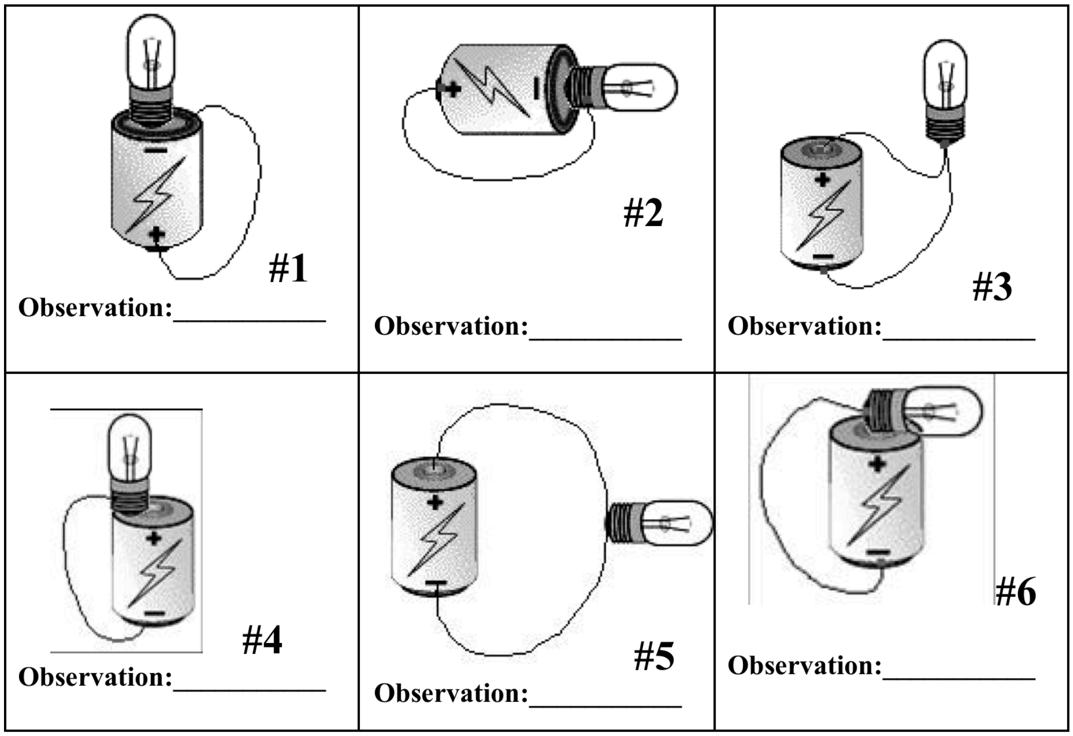


Figure 4: Activity prompt from Cave 1 in the Fall 2011 semester. Children are asked to write yes or no in the space provided to indicate if the bulb will light or not. The children are directed to conduct these specific experiments, and the structure of the activity is worksheet-like with fill-in-the-blank spaces for answers. This activity was drawn from the PET curriculum [36].

The content of the modified circuits curriculum is simple series electrical circuits. In the first set of activities (Cave 1), children predicted which pictures of configurations of wire and batteries would light a bulb, tested the configurations, and wrote rules to explain why each configuration would or would not light. Figure 4 shows an example of these prompts. In the second set of activities (Cave 2), students use their observations about how to light a light bulb to determine what the inside of a light bulb looks like, as in how the filament makes a complete circuit (see Figure 5).

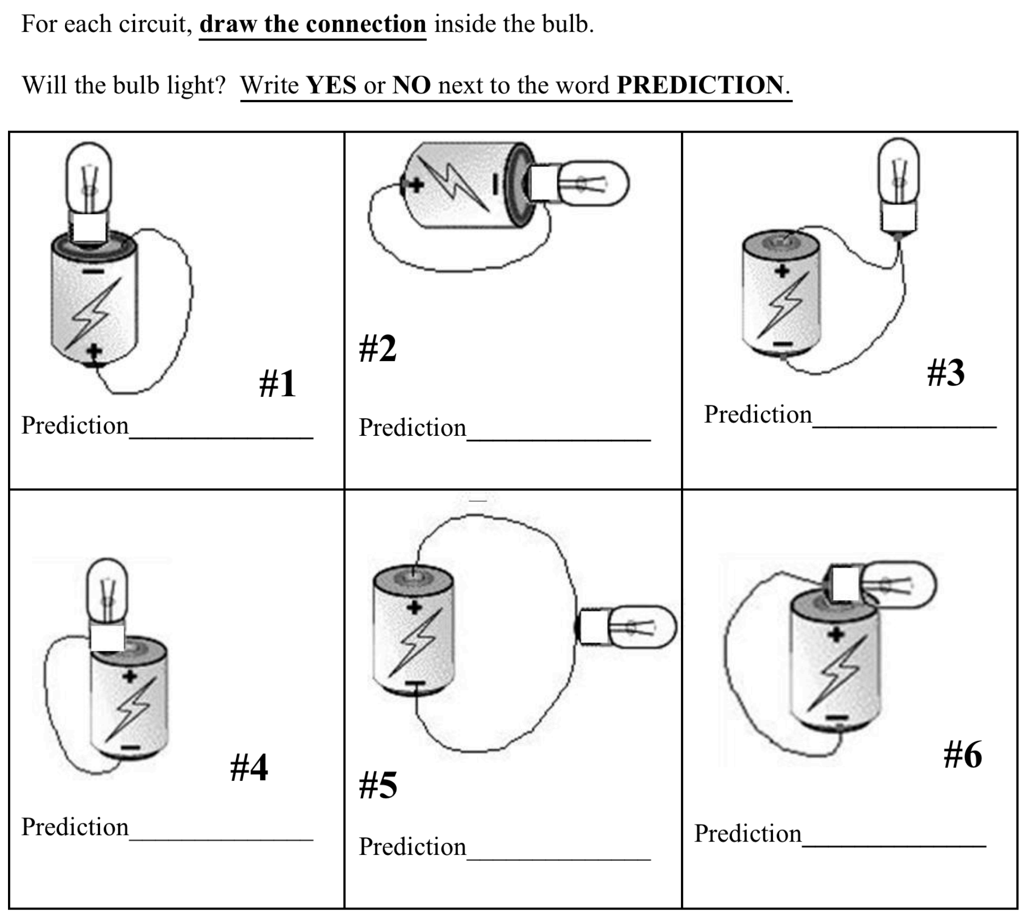


Figure 5: Activity prompt from Cave 2 in the Fall 2011 semester. Children draw in the connections from the outside of the bulb to the filament. This activity again has fill-in-the-blank prescribed areas for children to answer, and also asks specific questions for children to answer. This activity was drawn from the PET curriculum [36].

The activities in the third cave repeat what was learned in the first and second caves but adds the concept of a switch. Children are required to generalize what they have learned in order to light a bulb using a configuration with two wires instead of one. The three caves also include extra challenges that students could choose to complete. Children must complete either Challenge 1, Challenge 2, or both challenges before moving on to Cave 3. Challenge 1 asks students to examine a flashlight and determine how the circuit inside the flashlight works. In

Challenge 2, children put different materials inside a circuit to see which materials conduct electricity. Figure 6 shows a prompt from Challenge 1.

Cave 1 Challenge #2 of 4

Make a drawing of the flashlight showing the **circuit**. You must draw how the bulb is connected to the battery.

Figure 6 Activity prompt from Cave 1 Challenge. Children examine a flashlight and make a drawing of the circuit inside the flashlight. This prompt is less guided than the prompts in the Caves. This activity was drawn from the PET curriculum [36].

The prompts for the Caves are heavily structured. Children are told what questions to investigate – for example, as seen in Figure 4 children are told to determine if each bulb will light or not. Children are directly told to test each specific configuration, thus the prompt also directed the data to be collected. In Figure 7, an example of how students are asked to summarize findings is given, and shows how students are guided to summarizing their evidence. Students were also given strict procedures to follow when communicating their findings; most of the curriculum had students circle answers, write yes or no if the bulb would light, or fill in explanations in boxes. A few prompts ask children to draw; however, the prompt always instructs what to draw. According to Table 1 in Chapter 2, these features indicate a more guided curriculum. Furthermore, the structure of the curriculum offers little opportunity for learner choice, providing no spaces for children to pose their own questions, or to design their own investigations. The challenges incorporate more learner-structured investigations; however, these were located toward the end of the curriculum and few children managed to complete more than one challenge during a semester of afterschool sessions.

For each circuit, what do you think the rules are now? Do not change your answers. What do you think now? Write your **changes** here.

Circuit #	Lights?	Why?
1		
2		
3		
4		
5		
6		

Figure 7 Activity prompt from Cave 1. Children write their explanations in the box provided. Children are specifically answering what the rules are for how to connect a circuit. This activity was drawn from the PET curriculum [36].

4.2 Open Inquiry Curriculum

The new open inquiry curriculum was designed to be almost entirely composed of hands-on experiments or simulations. The new activities focus on light and optical phenomena, using a mixture of science toys, PhET computer simulations [38] and college laboratory equipment. For example, concepts about reflections are explored using a fiber optic lamp and laser chess game, along with a more typical setup where students measure angles of incident and reflected light using a laser and mirrors. The science toys, simulations, and laboratory equipment are chosen to be aesthetically pleasing to the children, meaning that the phenomena to be investigated may be beautiful or appeal to the fantastic. Appealing to aesthetics in the open curricula was done to foster excitement about science activities. According to Pugh, the buildup and consummation of anticipation is an important component of having an experience that transforms the way a person looks at the world [14]. Furthermore, the buildup and consummation of anticipation can help in making ideas personally worthwhile, which can strengthen reflective thought [14].

The structure of the activities was changed to be more learner-driven, giving the children more choice regarding how they interact with the content by allowing the children to pick the topics and activities they wished to investigate rather than forcing children to do activities in order. The style of the activities was also changed from the more worksheet-like prompts. The new activities consist of 3-5 prompts that fit on a quarter of a page of paper that could be taped into the lab notebook so that children were able to use most of the notebook page for documentation. Activities are a mixture of mostly open-ended questions and suggestions of specific items that children could draw or define. Figure 8 shows an example of two prompts in the more open curricula. The children are not forced to do any experiments; they get to choose what items to investigate. Also, the prompts were designed to give some examples of questions to answer, but the children are encouraged to answer their own questions; thus, the new curricula supports the learner posing their own questions as in the open inquiry section of Table 1 in Chapter 2. The way that children communicate their findings is mostly left to them. Within the more open prompts, children are occasionally asked to write or draw specifically - however, these occurrences are rare and learner choice in communication is still possible. Children are also not given guidance within the curriculum in formulating explanations from evidence. However, the university educators may guide children in formulating explanations, and the more open curriculum does depend more on the expertise of the university educators in helping children learn physics content. Learner choice in communication and lack of curriculum prompted guidance in explanations are components of Table 1, indicating a more open inquiry curriculum.

Experiment

Examine the fiber optic lamp.

1. **Write: How does the light get from inside the base to the ends of the fibers? What does this have to do with reflections?**
2. **Draw a picture of how you think the light gets from the base to the ends of the fibers.**
3. Guess how many fibers there are! **Write it down!**

Experiment

Examine the 3D Hologram chamber. Be careful not to leave fingerprints on the inside of the chamber!

1. Put in at least 2 different objects: try something shiny, clear or solid. **Write down what you see!**
2. Discuss: How do you think the chamber works?
3. Look at the diagram of the chamber. Discuss what it means with your group.
4. Try this! Take the bottom half of the chamber and move it from far away to close to your face. **Write: What happens to your reflection?**

Figure 8: Activity prompts from the more open inquiry curriculum. These prompts do not specify how to collect data or how to answer questions.

The children are asked the question "How does the light in the fiber optic lamp get from the base of the lamp to the ends?" This prompt does not instruct children as to how to collect data, what data to collect, or how to summarize their findings. It simply presents a question to answer, and the children get to choose if they even want to answer it. Furthermore, one of the choices children could make in the curriculum is to design their own experiment. When chosen, children tape in a prompt that simply reads, "Design your own experiment." These prompts create a space for the children to pose their own questions, determine what constitutes evidence and collect it, and decide how to communicate their findings. This activity demonstrates all aspects of open inquiry from Table 1. Children are given rewards for every two experiments they designed themselves. These rewards are scientific clothing such as clean room shoe covers, safety goggles, pocket calculators, and lab coats.

One note to acknowledge is that in describing the two inquiry curricula we have been using the terms open and guided. We would like to mention that there is a continuum between open and guided inquiry and the two curricula in this thesis are not dichotomous, with the guided curriculum being entirely on the guided side, and the open curriculum being entirely on the open side of the continuum. There are some activities in the guided curriculum that are more open and some prompts in the open curriculum that are more guided. As a whole, however, the overall environment and majority of activities are more guided in the guided curriculum and the overall environment and majority of activities are more open in the open curriculum. For simplicity we will just refer to the two curricula as open and guided.

While the optics curriculum was the first more open inquiry curriculum developed for PISEC, there now exist Newtonian mechanics, electricity and magnetism, and sound, fluids and thermodynamics activities following the same example as the optics curriculum. The new, more open environment has now been running for five semesters.

CHAPTER V

STUDY METHODS

5.1 Comparison of semesters

In this thesis, we compare the final semester of the guided inquiry circuits curriculum to the first semester of the more open inquiry optics curriculum. We also look at data from the first semester in which the optics curriculum was repeated. This thesis will focus on two locations that both ran the more guided curriculum in the Fall 2011 Semester, the more open optics curriculum in the Spring 2012 Semester, and repeated the more open optics curriculum in the Fall 2013 Semester. These locations, Laketown Middle School and Greenwood Middle School (names have been changed), are both urban middle schools in a city near Boulder. In both middle schools, PISEC partners with the MESA program [27] to recruit children to participate. We compare data from the same twelve students, 7 from Greenwood and 5 from Laketown, who participated in both the Fall 2011 circuits activities and in the Spring 2012 optics activities. In the Fall 2011 semester, Laketown Middle School had 12 regularly attending children and Greenwood Middle School had 15 regularly attending children. In the Spring 2012 Semester, Laketown Middle School had 9 children regularly attending and Greenwood had 15. However, some students did not return in the spring, and some new students joined in the spring. Thus we only study 12 students when comparing the more guided curriculum to the more open curriculum because only twelve students participated in both curricular approaches. During the Fall 2013 semester, 37 children participated in the repeated optics curriculum. Of these, 17 children were from Laketown Middle School and 20 children were from Greenwood Middle School. The children who participated in the repeated optics curriculum in the Fall 2013 Semester are all different from the 12 children studied when comparing curricula.

5.2 Notebook Analysis

The primary data source for this work is children's scientific notebooks. We define the scientific notebook like Primo et al., in that the notebook is a log, or composition of entries that provide a record of what the children are doing in PISEC [39]. Ruiz Primo et al. use scientific notebooks in formal school classes to not only evaluate students' performance in the class but also to evaluate the opportunities that the students are given in order to learn science. As an assessment tool, the notebook allows students a place to provide evidence regarding their science knowledge and understandings, gives a format for communication, and is a medium that can be scored and evaluated by the teacher [39]. Scientific notebooks can be used as an unobtrusive assessment tool [39], as in, a way of accessing student work that is different from high pressure exams.

In PISEC, children communicate their findings in a spiral notebook. Notebooks are passed out at the beginning of each session and collected at the end of each session. Children keep the same notebook for the duration of the semester and often reuse their notebooks over multiple semesters. Each activity prompt is taped into the notebook and children respond to prompts by writing in the notebook, generally answering questions on the prompt but also documenting everything they did with the equipment relating to the prompt. During Fall 2011 and Spring 2012, the children used their notebooks to communicate with a mythical wizard figure, and share their findings. The Wizard (who in reality was either the director of PISEC or one of the volunteer UEs) would write encouraging comments back to the children. The children would generally read the notes from the Wizard at the beginning of each session, and often wrote notes back to the Wizard.

Because PISEC is an informal environment, notebooks are evaluated instead of giving children exams like in a school setting. In the more guided curriculum, pre and post content tests were embedded in the curriculum. At the beginning of every Cave, children would be asked questions relating to the material, the children would then conduct the experiments, and the students would be asked the same questions again at the end of the Cave material. This was problematic, however, because the children often complained about seeing the same material three times. We believe the pre and post tests added to the children's complaints that the curriculum was too slow and "boring." Thus, in the more open curriculum, children are not given any pre or post tests and evaluation of the program relies solely on evidence in notebooks from the activities themselves.

We have developed ways to code for written and pictorial communication in order to study how the students communicated their scientific findings in the notebooks. We coded for instances where students exercise their freedom of choice to study agency, and we adapted a coding scheme previously used for discourse to study mechanistic reasoning used by children in their communication. In each of the following chapters, there is a more detailed explanation of the coding system that was used to analyze the major studies conducted: agency, communication and mechanistic reasoning.

5.3 Comparison of Activities

In the following chapters, we will be comparing agency, communication, and mechanistic reasoning between the two curricula, and in particular, we will be comparing activities between the two curricula. Thus, we must define what is meant by activity. An activity is a group of prompts referring to one particular phenomenon, piece of equipment, or concept. Both curricula grouped prompts this way. For example, Figure 4 shows how the guided curriculum grouped six similar predictions into one activity. Similarly, in Figure 7, the guided curriculum grouped written explanations for the six predictions into a different activity. Figure 8 shows how the open curriculum groups questions referring to the fiber optic lamp into an activity and questions referring to the hologram chamber into a separate activity. While there are differences between the activities in the open and guided curricula, we believe we can compare activities because they are both grouped in similar ways.

Another important note is that we compare activities that are circuits activities in the guided curriculum to optics activities in the open curriculum. Thus, the differences that we see between the two curricula could be due to the change in content instead of the change in structure. It is left to future analysis to compare agency, communication, and mechanistic reasoning between open and guided circuits curricula; however, from a cursory look at some circuits activities in a new open electricity and magnetism curriculum we believe that the notebooks from the two open curricula with different contents are more similar than the notebooks from the open and guided circuits activities. Figure 9 shows the responses of a child in a guided circuits activity and Figure 10 shows the responses of a different child in an open circuits activity. It can be seen that the prompts are very similar, but the children’s responses are very different.

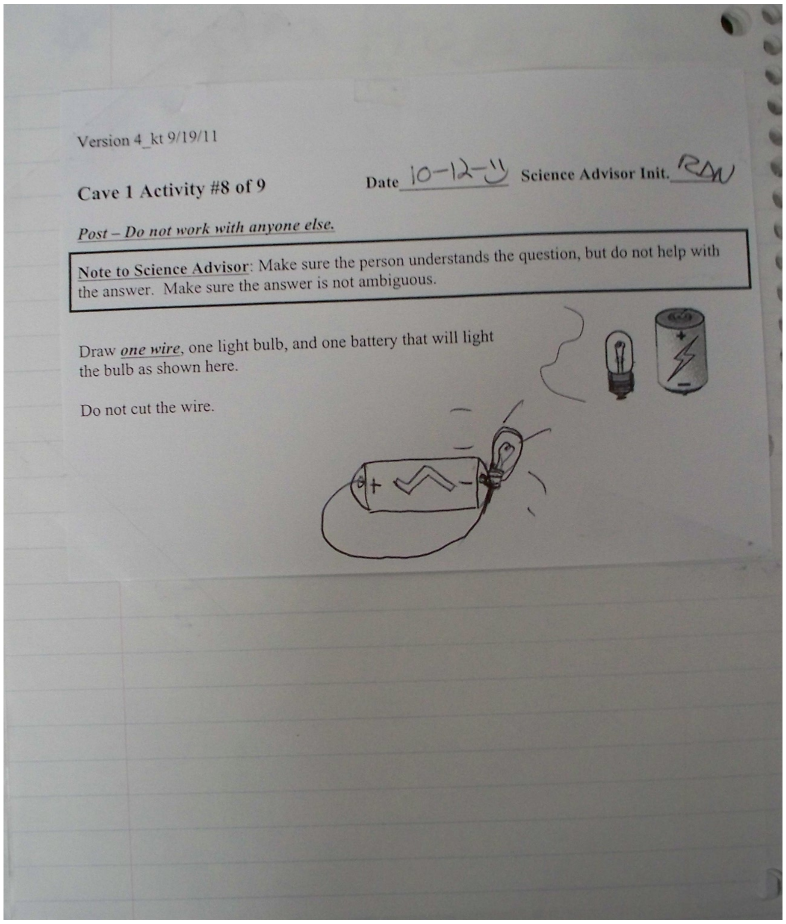


Figure 9 Example of children's work in guided circuits activity. The child only draws what is asked of her and does not fill the remaining space on the page.

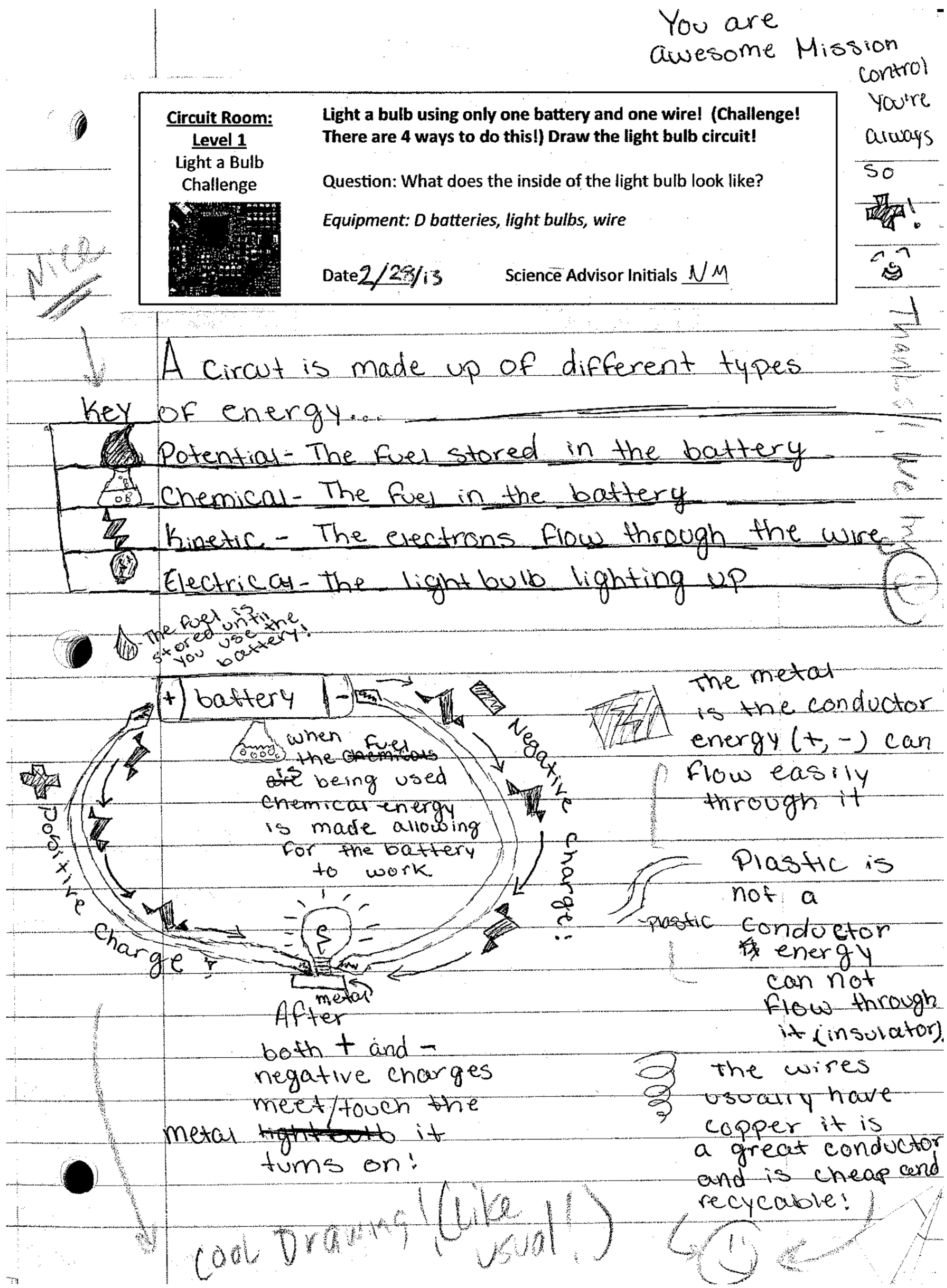


Figure 10: Example of children's work in open circuits activity. This child adds more than is asked for to the prompt and fills the entire page with writing and drawing.

CHAPTER VI

AGENCY

The National Research Council's definition of inquiry identifies a range of inquiry from open to guided [11]. In this definition, the more learner-directed the activity, the more "open" the inquiry. Learner agency, the extent to which a child exercises control over their activities, is an important feature in open inquiry. Research suggests, however, that inquiry tasks in schools are not giving learners the chance to practice authentic inquiry, but are rather giving students a false idea that the scientific method is "simple, certain, algorithmic, and focused at a surface level of observation" [40]. Authentic inquiry, on the other hand, is a key process that scientists use when practicing research. Many aspects of authentic inquiry fall within the NRC's definition of open inquiry, specifically: allowing the learner to chose what to investigate, how to collect data, and how to analyze results [11 & 40]. In PISEC, the more open curriculum is designed to give children more opportunities to choose how to conduct their investigations, or provide more student agency in the curriculum. In this chapter, we look for evidence of the children acting as agents within both curricula. We analyze how children choose their activities, and what they do in activities.

6.1 Choice of Paths Through Curricula

In order to probe opportunities for children to develop a sense of agency in PISEC, student trajectories through the space of possible PISEC activities were charted from dated activity worksheets taped into student notebooks [37]. A selection of student paths mapped onto the corresponding semester game board is shown in Figure 11.

In the guided curriculum, the conceptual complexity of circuit activities built in succession from one activity to the next (from cave to cave), and so all children started with activities in Cave 1, Level 1. After completing this level, which took between 2-3 sessions, children were offered their first choice between moving to Cave 1, Level 2, or skipping to Cave 2, Level 1. Over 80% of students chose the path that did not skip the second level of a room and was thus necessarily identical to the paths of the other students.

In the open Spring 2012 curriculum, the activities were organized into five topic areas, or rooms (Reflection, Bending, Rainbow, Image and Bonus Rooms) with three levels each. Students started at Level 1 in the room of their choice; upon completion of the associated activities, students could continue to Level 2 in the same room (a vertical move), or switch to a different room (a horizontal move). Around half the students chose to make only vertical moves, that is completing all the levels in a room before moving to the next room – similar to the strategy most students used in the earlier circuits curriculum. A quarter of students chose to complete all of Level 1for the game, moving room to room, while the other quarter of students chose a combination of vertical and horizontal moves so that their path around the game board was more random. Thus, when provided with more choices, children made more choices about what activities to investigate.

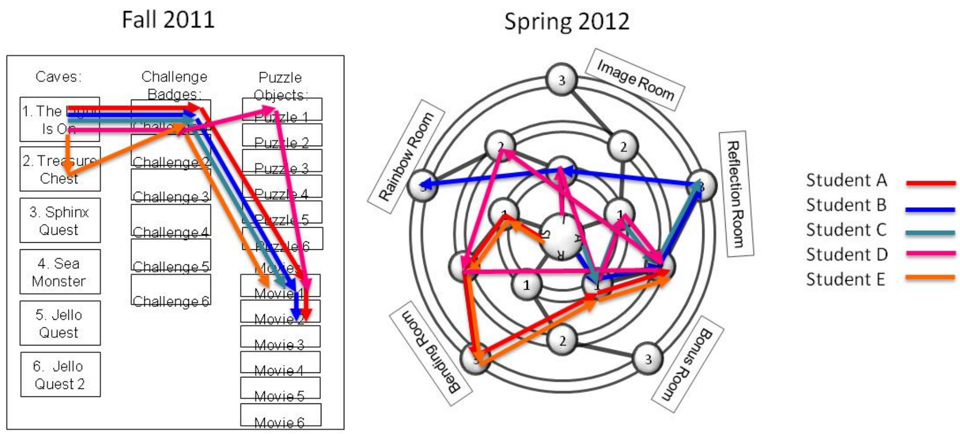


Figure 11: Children's choice of path among activities (figure shows 5 out of 12 children's moves). The image on the right shows the choices children made in the more guided curriculum, indicating fewer differences among paths. The figure on the right shows the right shows the choices children made in the more open curriculum indicating that children are choosing different paths from each other.

6.2 Student Agency in Activities

To determine the amount that children were exercising agency within the activities themselves, student responses to the activity prompts were examined for student-directed behavior in three categories, children *following prompts*, children adding *additional information to prompts*, and children *designing their own experiments* [37]. For the first category, instances were counted when children answered all or most (all except one) of the prompts for an activity. In the second category, instances were counted when children added scientific information that the prompts did not ask for directly. Depending on the activity, this non-prompted information could include drawings, further observations, notes about procedure, descriptions of how the outcome would change if the experiment changed, or a description of a non-prompted activity. Figure 12 shows an example of non-prompted information in a child's notebook.

Open the PhET simulation, ***Color Vision***, on the computer.

1. Play with the simulation for 5 minutes. Time yourself with the stopwatch! (If you want to add 2 more minutes, do it!)
2. Discuss with your group how you think you could make white light.
3. Now do it! Make white light.
4. **Write how you made white light.**
5. Discuss with your group what white light is made of?

Science Advisor Initials _______

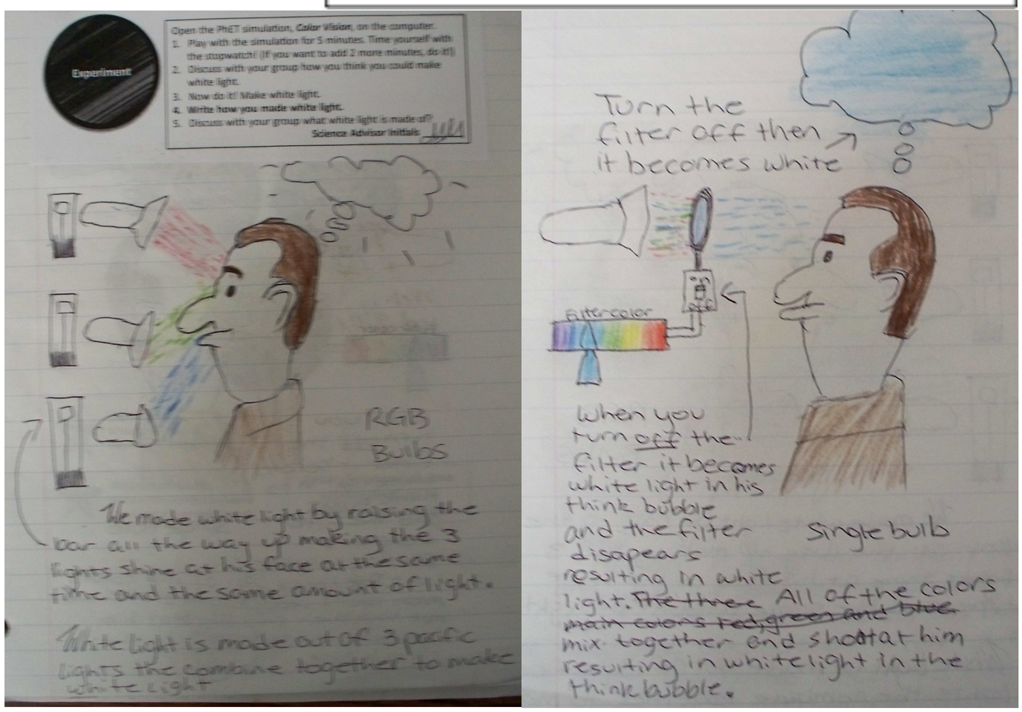


Figure 12. Prompt for “Color Vision” activity. Activity prompt from the more open curriculum (above), and one child’s response (below). The response on the bottom left answers the prompt, stating how white light is made but adds a non-prompted picture of the simulation. Response on the bottom right details the child’s non-prompted interaction with the simulation, exploring the filter settings.

The prompt does not ask for a picture of the simulation making white light. The prompt also does not ask children to explore the simulation using the filter. An important note is that children could receive no points for the first category, following few prompts, and still receive a point for the second, adding information not asked for. The third category was the number of times children designed their own experiment. In Fall 2011, there was no specific activity in which children were given the chance to design their own experiment. Thus, the coding for Fall 2011 was for experiments written between activities that were different from any activity. For example, one child wrote that she had tried putting two batteries in series with one light bulb. This reported action was counted as a designed experiment. Another child wrote in an observation that the wire became hot when she was testing the configurations in Cave 1. The latter example was not counted as a designed experiment but as non-prompted additional information. In Spring 2012, the child-designed experiments were given a special demarcation in the notebooks, called "Big Ideas." Thus we coded all big idea prompts as child designed experiments. When children used equipment from an activity in a way that was not prompted in an activity, it was not counted as designing their own experiment unless the child chose to include a Big Idea prompt.

Figure 13 shows the results of this analysis. We find that the children follow the more open curriculum prompts less frequently than they do with the guided curriculum. However, children add some non-prompted scientific information three times more in the open curriculum compared to the guided curriculum, with additional information being added to 1 out of 3 activities. Furthermore, there were six times more instances of children designing their own experiment in the open curriculum, with 1 out of every 3 activities leading to a Big Idea. These numbers indicate that in the more open curriculum children are not being directed by the prompts as much as in the more guided curriculum. Instead of answering questions that the curriculum is asking, children often make up their own questions to answer.

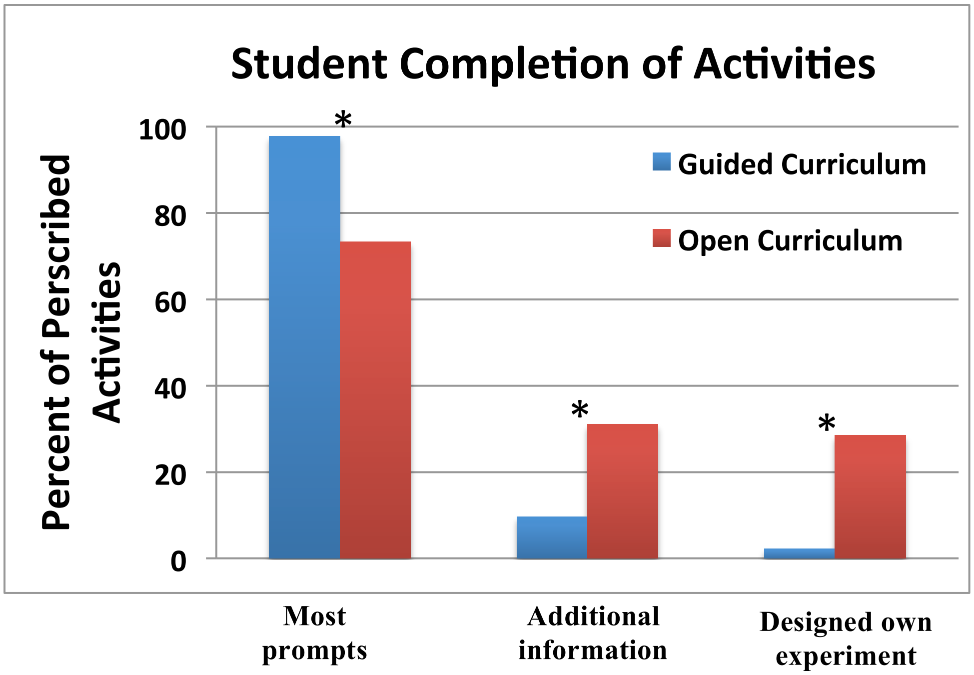


Figure 13: Student completion of activities. Comparison of guided curriculum to more open curriculum in student completion of activities. Y-axis shows percent of total prescribed activities for the following categories: Children followed most prompts, children added additional information, and children designed their own experiments. Stars indicate a significant difference between proportions, p ≤ .01 [41].

6.3 Discussion

In making the curricula more open, we attempted to provide the children more opportunities to exercise their own agency. We find that children take up these opportunities and in fact exercise more agency in the open curriculum. Children are given more options in how to move through the game system, and they choose more varied paths through the game system. Children are also not following the curricular guidance as much, but they are making up their own questions to answer, and are deciding how they want to communicate their ideas, adding additional information and designing their own experiment in about 1 out of every 3 activities. Hazari et al examines physics identity with the dimensions of student performance, competence, recognition by others, and interest [10]. According to a study conducted by Hazari et al, some practices can positively influence physics identity in high school students. These practices include focusing on conceptual understanding, making real-world connections, countering stereotypes that physics is a one-dimensional pursuit that requires giving up other desires, getting students to take on active expert roles, and encouraging students [10]. We consider children exercising more control over their activities as evidence that they are taking on more active expert roles in their scientific investigations. Children taking on active expert roles is a practice that supports positive physics identity development, and thus our switch from a guided curriculum to a more open curriculum has supported our goals of developing strand six of informal learning environments, for children to develop an identity as someone who knows about, uses, and contributes to science.

CHPATER VII

COMMUNICATION

Communicating scientific ideas and investigations with peers is a significant component of scientific inquiry [11]. Furthermore, keeping records and writing journal articles is a necessary undertaking that professional scientists must perform as part of a scientific community of practice. Practicing the construction of scientifically appropriate communication helps learners understand science content as well as involves the learner in an important science practice [39]. In PISEC, children are encouraged to write in their notebooks, but the type of communication is largely left to them. We look at the communication seen in the children's scientific notebooks in PISEC in order to analyze how the curricula foster communication.

7.1 Amount of Communication

Almost all scientific representations in the children's notebooks were classified as either writing or drawing (for instance, we found no instances of the children using equations, and few used a table). We compare the total number of words the children used in the guided curriculum to the total number of words the children used in the more open curriculum. Because some children wrote more in their notebooks than just words related to activities (such as writing to the Wizard and writing nonsense) only the words related to activities were counted as scientific words. We also compare the number of drawings in the guided curriculum to the more open curriculum, with only drawings related to activities coded. The children's pictorial representations were counted by only allowing one count for drawings per activity because activities are chunked so that each activity refers to one experiment or phenomena. Also, some drawings that had multiple parts, like a wide view and zoomed-in view of the same apparatus, and some drawings were unclear if they were part of one drawing or multiple drawings; thus, only one count is given for drawings per activity to avoid counting one picture as two pictures.

Both scientific word and drawing counts were averaged over the total number of activities completed during the semester, including activities where children designed their own experiments. As seen in Figure 14, on average, the children wrote more and made more drawings related to the activity in the open curriculum. The children spent roughly the same amount of time doing activities both semesters.

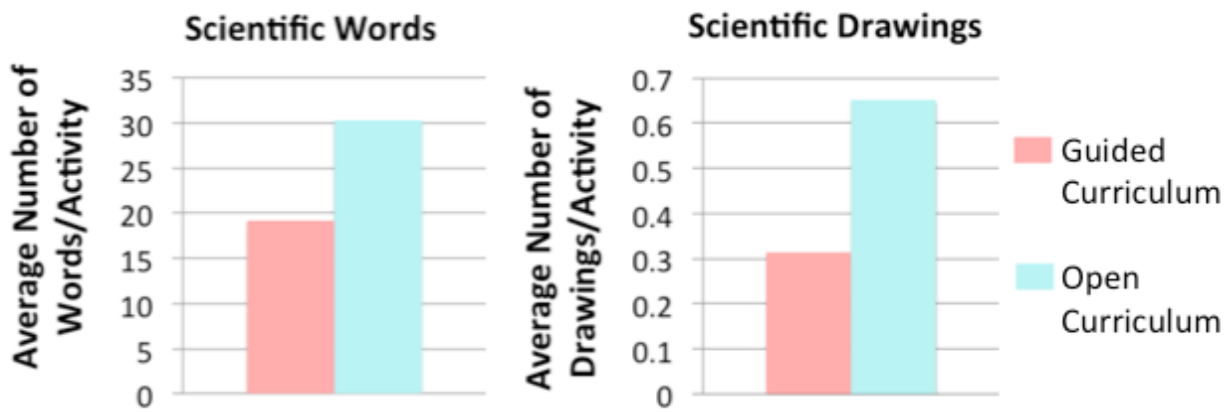
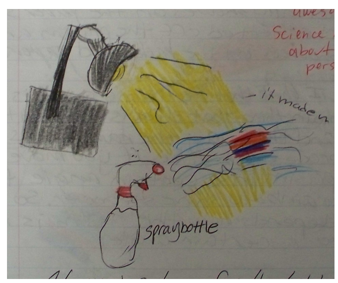


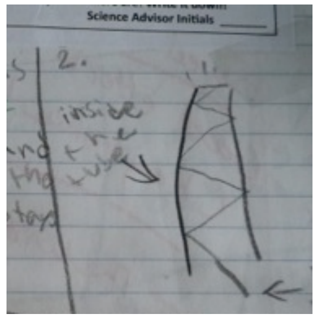
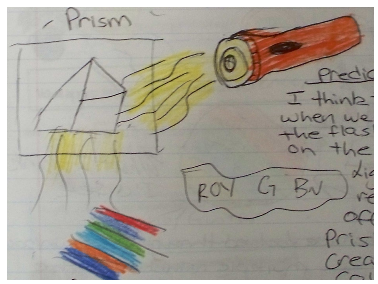
Figure 14: Average number of words per activity (on the left), and drawings per activity (on the right). Both the average number of words and the average number of drawings per activity are significantly greater in the open curriculum compared to the guided curriculum. ($P < .0001$ using a T-Test for the word count and $p \leq .01$ for the drawing count according to a difference between binomial proportions test.)

7.2 Communication types

While we see that children wrote more words and drew more pictures in the open inquiry curriculum, it is also important to look at the content of these representations. Ruiz Primo, et al. evaluates students' notebooks by analyzing the types of notebook entries in school settings [39]. We apply and expand on this coding scheme for notebooks in PISEC. Ruiz Primo describes two genres of notebook entries, major and minor. Major notebook entries are detailed, complex and long, such as final lab write-ups. The minor genre consists of shorter, simpler and less formal forms of communication [39]. While the major genre entries are expected in a formal school setting where students are specifically being asked to write lab reports, they are not seen in PISEC. PISEC is an informal environment where the children are not expected to write any long pieces. Instead, children communicate scientifically by jotting down their ideas and experimental results in their notebook without any specific formatting; thus, PISEC notebooks entries fall more into the minor genre. Ruiz Primo lists the types of entries in the minor genre as: Defining, Exemplifying, Applying Concepts, Predicting/Hypothesizing, Reporting Results, Interpreting Data and/or Concluding, Reporting and Interpreting Data and/or Concluding, and Content Questions/Short Answer Quick Writes [39]. The last type of entry is specific to the school setting and is not seen in PISEC. *Defining* is the act of writing down a definition to key vocabulary. Definitions of words are rarely seen in the main body of the children's notebooks because children play a game in which they catch university educators using big words and then write definitions to big words in the back of their notebooks. Children are awarded with stickers for every big word they find. In PISEC, we do not directly teach concepts, but instead allow children to discover concepts on their own. Thus, *Applying Concepts* does not show up in our notebooks. We do see the categories of *Predicting/ Hypothesizing*, *Reporting Results*, and *Interpreting Data*. We also see children *Reporting Procedure*. Ruiz Primo defines *Reporting Procedure* as a major genre, but since we see short instances where children report their procedure in PISEC, we include it in our coding scheme. Additionally, we see specific ways that children predict/hypothesize, and interpret data in PISEC; thus, we have split the categories that Ruiz Primo uses into more specifically defined subcategories. We also see communication that does not fall into Ruiz Primo's categories. We present our codes, the description of our codes, and examples in Table 2. Because each activity is chunked to look at only one experiment or phenomena, we only code each type of communication once. This information tells us what type of communication is found in each activity but does not give an amount of each type of communication per activity. To test for inter-rater reliability, two researchers coded six of the notebooks and achieved agreement on 89.8% of the codes. One researcher coded the remaining 31 notebooks from only the Fall 2013 semester.

Table 2: Code names, descriptions, and examples for communication types. The table shows Ruiz Primo et al.'s categories broken into subcategories that are relevant to PISEC.

Code	*Description*	*Example*
Reporting Procedure		
Verbal	*Children explain their procedure in words. This can be a description of all or part of their procedure. This is often not very detailed.*	 *To test if a rainbow can be seen at a distance a child wrote, "I will have my partner help me. She will keep moving back from me while I will spray water out the bottle."*
Picture	*Children draw a picture that shows how the experiment is set up, or depicts what to do in order to produce the phenomenon.*	*This picture shows how the children sprayed water by a lamp to make a rainbow. This picture shows procedure and results (a rainbow).*
Developing a testable question	*Children state a question that they can test. Generally the children also test their questions, but this is coded when children just state a testable question as well.*	*Some questions children asked in their notebooks were: "Can you see a rainbow from a distance?" "What if I put a laser under the fiber lamp instead of the big blue one [light]?"*
Predicting/hypothesizing		
Explaining	*Children explain why a phenomenon occurred. This writing does not have to be a correct or deep explanation and often is a guess.*	*When prompted to figure out why the magnifying glass makes things look bigger one child wrote "It has a special kind of glass that it lets you see things bigger than normal" When asked to explain why the hologram chamber produces a hologram one child wrote, "I think it [light] bounce in the mirrors."*

Predicting	*Children make a prediction regarding the outcome of their experiment.*	*When predicting what will be seen through a magnifying glass one child wrote, "I think that it will be easier to see the arm hair with a magnifying glass than with my eyes."*
Picture of unseen mechanism	*Children draw a picture that shows how a phenomenon occurs including a depiction of an agent that is not visible to the naked eye.*	 *This picture shows the lines of reflection that occur inside a fiber optic cable. The children cannot actually see the reflections inside the tube but they inferred that the light gets from the base to the ends of the fibers by reflecting inside.*
Reporting Results		
Picture	*Children draw a picture of either their entire set up including the results, or just a picture of the results of the experiment.*	 *In this picture the procedure, shining a flashlight on a prism, is depicted and also the result, a rainbow, is depicted. These representations would be coded as a picture of the set up and a picture of the results. If just the rainbow were drawn, it would be coded as just a picture of results.*
Verbal	*Children state in words the outcome of their experiment.*	*When holding two mirrors together one child described what he saw "yo could see a lot of mirrors, yo see like 30 mirrors."*
Table	*Children list data in a table*	*Children must specifically draw a table and fill it with observations or data.*
List of trials	*Children make different trials of an experiment changing a variable and list the outcomes of each trial. If children reported the results of three trials then the notebook would only be coded once for reporting results and once for a list of trials. The list of trials code was added to as to not have to count each trial as a separate procedure and results when the procedure was almost identical and the results similar.*	*Children looked through a spectroscope at three or four different light sources. Many children listed each experiment and drew a picture of each spectrum. These representations were coded as verbally reporting procedure and pictorially reporting results only once because all of the procedures were basically the same and pictures were very similar.*

Interpreting data		
Summarizing	*Children summarize their results. Children may or may not also state their results. If they state their results as well as summarize the notebook would be coded for reporting results and summarizing results.*	*When comparing different lenses one child wrote, "Depending on the thickness and angle of the glass it had different magnification." This statement summarizes his results from looking at various different lenses.*
Direct comparison in experiment	*Children compare two or more trials of an experiment, or compare before and after an experiment.*	*While examining lenses one child wrote, "The fat lens makes things small and the skinny lens makes things big," thus directly comparing the fat lens to the skinny lens. When looking through a magnifying glass another child wrote, "when I look at everybody they look normal but when look [through] the magnifying glass every body looks big," thus comparing the before and after of an experiment.*
Comparing to something else	*Children identify that one phenomenon is like another, or that a phenomenon is like something they have experienced in their life.*	*When talking about microscopes one child wrote, "we talked about how the microscope and the eye exam are similar. For example, the part where you put your eye is the same." This child compares the microscope to something she encounters in her life, the eye exam.*
Other		
Showing enthusiasm	*Children make a comment or write in a way that demonstrates enthusiasm or excitement.*	*Many children added multiple exclamation points to their writing, many children added words like "cool," and "awesome," and some children wrote comments to Mission control or the Wizard like the following, "I got shoe booties… thxs."*
Making additional observations	*Additional observations are important observations that children make that are related to the experiment but aside from or in addition to the experiment they are working on.*	*One child was trying to burn tape by focusing sunlight through a magnifying glass. She noticed that the sun was not overhead and connected it to her magnifying glass experiment. "The sun was bein a litta lowa but the tape was getting hot." Another child was using the PhET simulation color vision and turned all of the lights on full blast. He remarked that, "full blast looks like it's burning his eyes." This comment is an observation about intensity, which did not directly have to do with the simulation that explored how colors are made.*

Once we identified the types of communication that children use in their notebooks, we looked at the average use of each type of communication in the notebooks from the Fall 2013 semester at Laketown Middle School (n = 17 children) and Greenwood Middle School (n = 20 children). We have only analyzed the semester in which we repeated the open optics curriculum as this coding system was developed using the Fall 2013 notebooks. We see that children are using a variety of different communication types in their notebooks, with an average of 3.5 $\pm$ .3 (standard error) different categories of communication, of the 15 defined above, per activity. We also counted the average amount the prompts the children completed specifically called for a type of communication. For example, most of the prompts are simply suggestions to help children start experimenting with a particular artifact, however, some prompts specifically tell children to draw their set up, draw what they see, or write their how they made a phenomena occur. These specific requests would be coded as *reporting procedure* with a picture, *reporting results* with a picture, and *reporting procedure* verbally. Figure 15 shows the weighted fraction average of each type of communication per activity. It is to be noted that no type of communication appears in every activity. We do not expect children to be using the same categorical type of communication in every activity; we expect that children will use different types of communication depending on what they wish to share in their notebooks. We see that children most frequently report their results verbally and in pictures, followed by children reporting their procedure verbally and in pictures. We also see that children rarely use tables to report their results, but more often use a more informal list of trials. Figure 15 shows that the children explain the phenomena on average less than the prompts ask. However, children also record their procedure, predict, and draw pictures to report results more than they are prompted to do so. Furthermore, we see six types of communication that are not asked for at all in the prompts, including drawing a *picture of an unseen mechanism*, *verbally reporting results*, making a *table* or a *list of trials*, showing *enthusiasm*, and making *additional observations*.

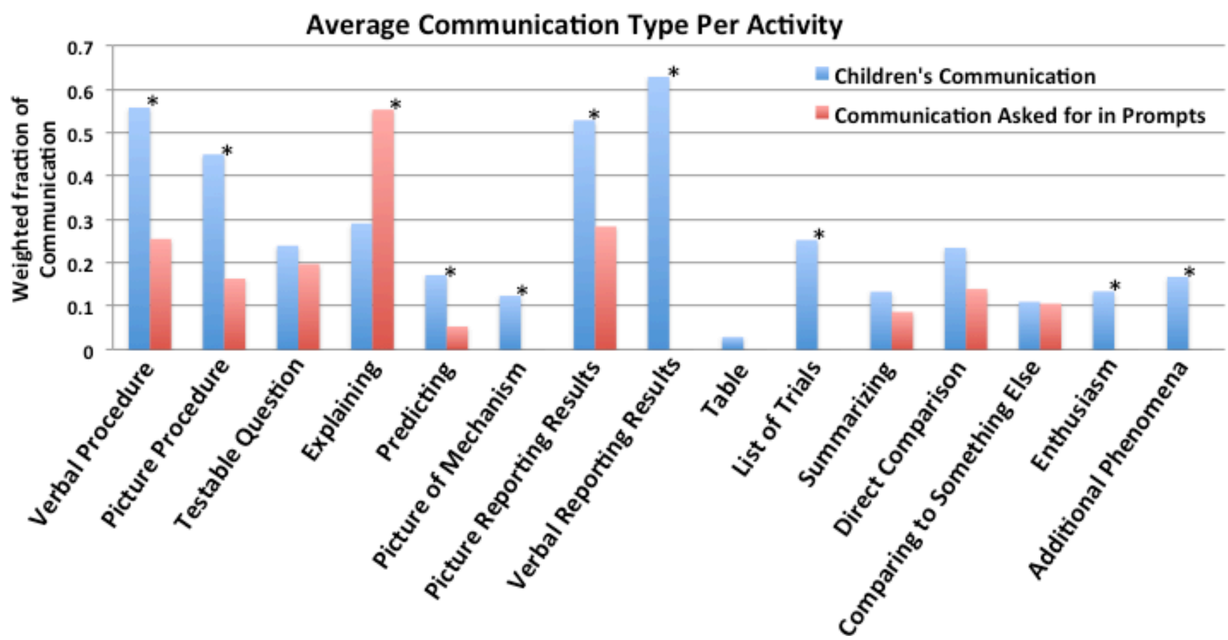


Figure 15: Average communication type per activity. Comparison of average prompted communication per activity that children completed and weighted fraction of each communication type per activity found in children's notebooks in the Fall Semester 2013 for 208 total activities. The graph shows that children are using many different types of communication in their notebooks, and are even communicating more than they are prompted. Stars indicate a significant difference between proportions, $p \leq .01$.

7.3 Discussion

We have seen that students write and draw more in the open curriculum compared to the guided curriculum. We also see children using a wide variety of types of scientific communication in their notebooks as well as even communicating more than they are prompted. According to research done by Calabrese Barton, et al., science learners must have some ideas of what it means to participate in the community in which they learn [42]. Learners can choose to formulate their views on what it means to do science in alignment to what is being taught in their community, or in opposition to what is being taught in their community. Learners can also choose to participate or not to participate [42]. Children in PISEC are often resistant to writing down their scientific activities because they may have difficulties reading and writing, they might rather be engaged in physically examining scientific equipment, or they may not see the value in documenting their observations and conclusions. However, children are still participating in this scientific practice that is taught in PISEC, and are participating more in the open curriculum. Children are participating so much they are communicating even more than they are required. Participation in the practices that are valued in PISEC as scientific practices is evidence that children are authoring identities in alignment with their perception of scientists regarding communication. There are other dimensions prevalent to how children author identities in alignment or out of alignment with their perceptions of scientists; we have just focused on communication in this chapter.

Furthermore, PISEC is providing the children with a unique opportunity to practice a wide variety of scientific communication. Studies suggest that having experience with communication is linked to school success in reading and writing [43]. The wide variety of scientific communication that we document in the children's notebooks might be related to the way that communication is valued in PISEC. Children are not only encouraged to write in their notebooks but also to talk about their ideas and findings with other children and with the University educators.

CHAPTER VIII

MECHANISTIC REASONING

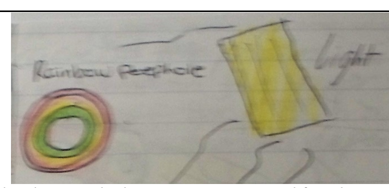
One type of reasoning seen in scientific inquiry is dubbed *mechanistic reasoning*. Reasoning that is mechanistic describes the underlying mechanism, and each of its sequential stages, that gives rise to phenomena [44]. When reasoning this way, children are formulating a model to explain what caused a phenomenon. Central to this style of reasoning are entities and activities. Entities are the constituent pieces that interact in activities to produce phenomena. For example, one phenomenon the children investigate in PISEC is a fiber optic lamp. The children often communicate the model of light bouncing off the walls of the fiber optic cable to emerge out the end. In this case, the entities are the light and the walls. The activity is the light bouncing off the walls.

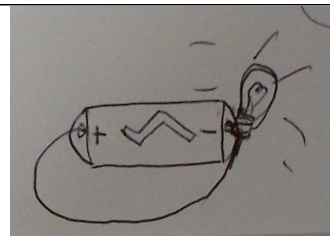
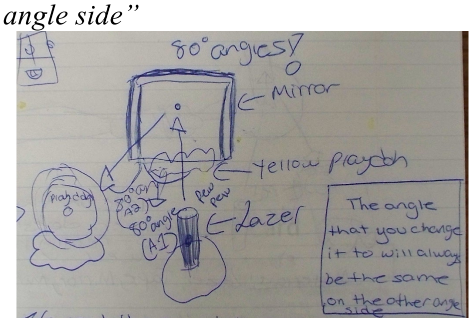
Mechanistic reasoning can play an important role in scientific inquiry. In many science classrooms emphasis is placed on learning what is "correct" based on what is written in a textbook [45]. This focus directly contrasts with how scientists analyze proposed explanations. When using an inquiry approach, one must not choose to accept ideas simply because they are supported by an authority or textbook, rather one must accept ideas based on evidence, models, and arguments that support the ideas. Mechanistic reasoning can be used to formulate an argument or model about the causes underlying physical phenomena [45]. This process is aligned with one of the essential features of and calls for inquiry lessons: learners formulate explanations from evidence [11]. In this chapter, we modify and apply an established coding system to analyze how the children's use mechanistic reasoning in PISEC.

8.1 Coding for Mechanistic Reasoning

We closely follow the coding scheme developed by Russ, Scherr and colleagues, which they used to analyze mechanistic reasoning in elementary student's scientific classroom discussions [44]. To apply this coding rubric to written documentation in the context of PISEC, we adapted eight of their nine categories of mechanistic reasoning. The ninth category, related to body language and gestures, was not captured in our data collection as we were only looking at written work. Table 3 summarizes our interpretations of and modifications to the mechanistic reasoning coding scheme.

Table 3: Interpretation of the categories for mechanistic reasoning. Adapted from Russ et al [44] as applied to PISEC science notebooks.

Category	***Description***	***Example***
1. Describing Target Phenomena	*Children state, make a prediction about, or draw the outcome of their experiment or phenomena that they observed.*	 *This picture is a prediction of what this child thought she would see through a diffraction grating.*
2. Identifying Setup Conditions	*Children state what they did before they started the experiment to make the outcome happen, mention their setup, or mention changing their setup.*	*When attempting to make a rainbow by spraying water near a lamp, one child wrote, "we tried various angles of where to spray and we discovered when we spray the bottle closer to the lamp it creates a strong rainbow."*
3. Identifying Entities	*Children specifically list or draw entities they are working with in their experiment without detailing their interactions.*	 *This picture depicts the entities involved in looking through the diffraction grating, namely light and the grating itself. The picture does now show how the entities interact.*
4. Identifying Activities	*Children explain how the entities interact to produce the phenomena or result of their experiment or draw a picture of an entity doing an action. Generally involves the use of a verb to describe an action the entities were engaged in.*	*When asked how the hologram chamber works, one child wrote, "I think the chamber works by the mirror thing in it bouncing the objects reflection off the sides until it reaches the top and creates the object's reflection." In this example the student identifies that the mirror and reflection are entities and the reflection bounces off the mirror.*

5. Identifying Properties of Entities	*Children state, or explain with pictures, what properties an entity has that make the phenomena or outcome of their experiment happen. We use this code whenever properties of either entities or phenomena in the system are described.*	*While examining how a laser can reflect off of a mirror, one child wrote, "Anything shinny can reflect off of something. Play dough, sticky notes, and solid items do not reflect." In this example, the child is indicating that objects that can reflect light all have the property of being shinny.*
6. Identifying Organization of Entities	*Children state, or draw a picture detailing, how entities must be spatially organized in relation to each other to make the phenomena happen or the experiment work.*	 *This picture is of a light bulb a battery and a wire connected to make a complete circuit. The specific way the entities (light bulb battery and wire) are organized in order to make a complete circuit is important.*
7. Chaining	*Children put together what they learned in an activity or series of activities to make a prediction about what should happen or formulate a rule that should hold in the future, predict what changes must have occurred in the entities to give rise to a new phenomenon, predict what entities must be interacting to make a certain phenomena happen, or hypothesize about what activities entities could do to make a new phenomenon.*	*In an experiment to determine how the angle of incidence is related to the angle of reflection one child took measurements for different angles and wrote, "we changed the positions of the way our setup was and we measured the angles. 50º angle 50º angle." The child then generalized the rule by writing "The angle that you change it to will always be the same on the other angle side"*  *The rule written is coded as chaining.*
8. Analogy	*Children compare the target phenomenon to another phenomenon.*	*When talking about microscopes one child wrote, "we talked about how the microscope and the eye exam are similar. For example, the part where you put your eye is the same." This child compares the microscope to something she encounters in her life, the eye exam.*

For each activity the children worked on, we identified what categories of mechanistic reasoning they used to describe what they were doing. For each activity we only identified if each category was present or not present; we did not count the number of times each category of mechanistic reasoning was used in each activity. We chose this counting scheme because most activities were chunked to explore only one particular phenomenon, and thus we were unable to tell the difference between multiple counts of the same type of reasoning within an activity. Two researchers discussed the codes in four notebooks until they agreed on all codes. One of the two researchers coded the remaining twenty notebooks of the Spring 2012 semester.

8.2 Mechanistic Reasoning Exhibited by Children in Notebooks

In order to compare mechanistic reasoning between the more guided (Fall 2011) and more open (Spring 2012) inquiry curricula, we counted the total amounts of the 8 types of written reasoning aggregated for the same 12 students over the course of the Fall 2011 and the Spring 2012 semesters [46]. The more open curriculum had 28.6 $\pm$ 7.2 total counts of reasoning per student, and students in the guided curriculum exhibited 25.4 $\pm$ 4.8 total counts of reasoning per student (error is standard error), so there is no statistical difference between the total reasoning. Because the children spent roughly the same amount of time in the PISEC program in the Fall 2011 semester and the Spring 2012 semester, we expect that the total amount of reasoning should be comparable. However, because the nature of the program changed to be more hands-on and less worksheet-like, we observed that children spent more time touching and playing with equipment and conducting experiments and less time writing in their notebooks in the open curriculum. Thus, we believe that the children actually had less time to document mechanistic reasoning in the more open curriculum - yet the total written reasoning is comparable. Also, the children completed more total activities in the guided curriculum (211 activities) than in the more open curriculum (128 activities). These values indicate that each activity in the more open curriculum took the children more time to complete.

While we do not find a difference in the total mechanistic reasoning between the two curricula, we do see a difference in the types of reasoning. As seen in Figure 16, the more open curriculum had more varied types of reasoning, and we find a significant difference in the two populations using a contingency table analysis ($p < .001$) [41].

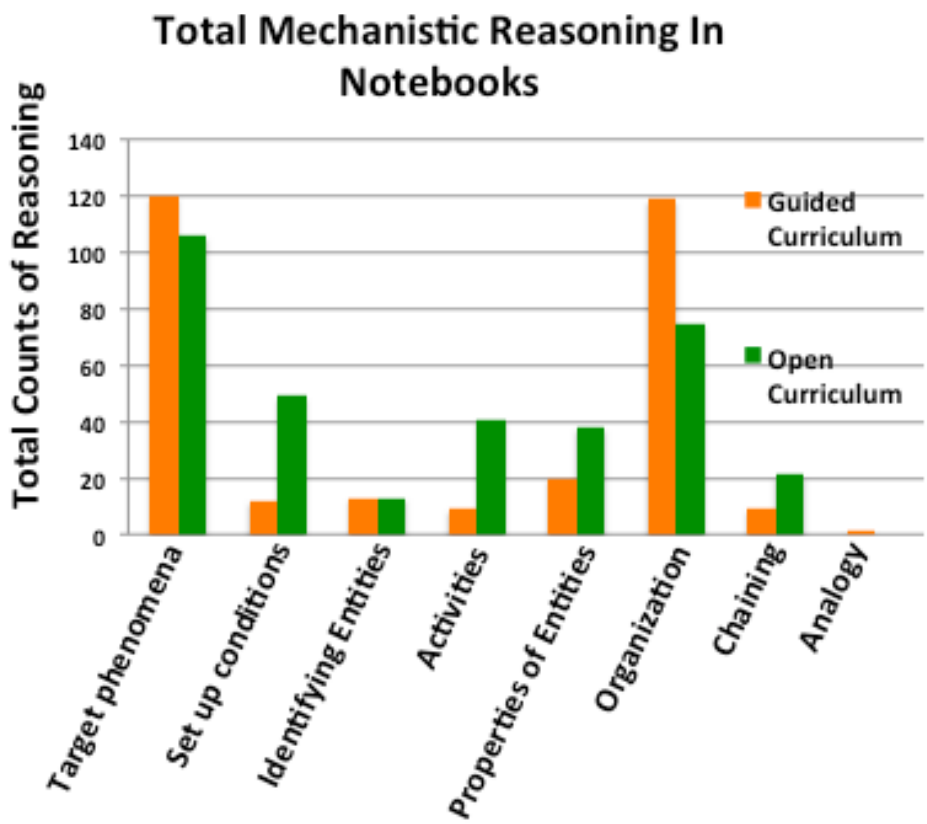


Figure 16: Total reasoning in notebooks. Comparison of written reasoning exhibited by students for guided curriculum (Fall 2011) and open curriculum (Spring 2012). A contingency table analysis shows a significant difference between populations, $p < .001$.

While there were more instances of *identifying organization of entities* in the guided curriculum, there were more counts of *identifying setup conditions* and *identifying activities* in the open curriculum. We also note that we counted answers to the activity in Figure 4, where children wrote yes or no to indicate if the light bulb lit up or not, as *describing target phenomena*. This may have over counted the instances of *describing target phenomena* in the guided curriculum because a yes or no answer is not a description of the phenomena and we cannot tell for sure if the children actually did the experiment. However, we decided to count these answers as *describing target phenomena* because children are answering questions about the phenomena of lighting a light bulb.

To further probe the differences between the open and guided activities, we also looked at the average mechanistic reasoning per prompt as seen in Figure 17.

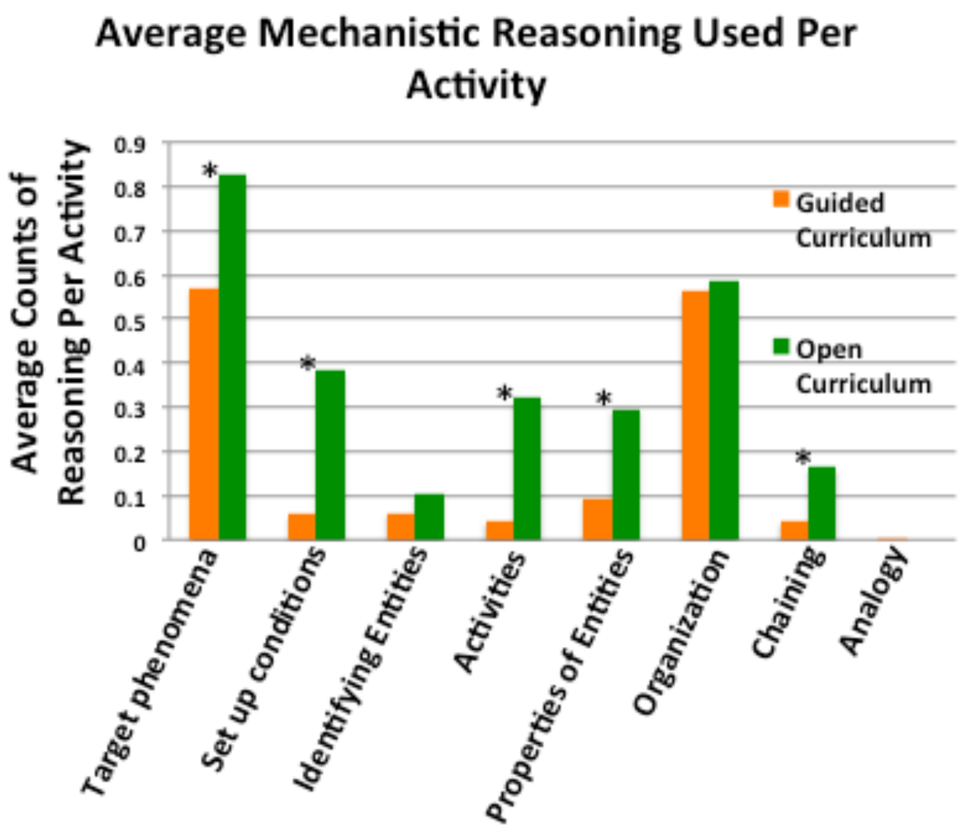


Figure 17: Average counts of mechanistic reasoning per activity. Children reason more per activity in the open curriculum compared to the guided curriculum. Stars indicate a significant difference between proportions p $\leq$ .01.

We find that on average children documented 1.4 $\pm$ .1 mechanistic reasoning codes per activity in the guided curriculum, compared to 2.7 $\pm$ .2 (standard error) mechanistic reasoning codes per activity in the open curriculum, a significant difference $p < .001$ (using a T-test). Thus, in the open curriculum, children are reasoning more per activity.

8.3 Mechanistic Reasoning Opportunities in the Curricula

In order to analyze the opportunities presented to children for mechanistic reasoning, we analyzed the prompts that were asked in each activity that the 12 children completed [46]. For each prompt, we determined which types of reasoning could be used to formulate an answer to each question based on the language of the prompts. For example, a prompt in the Spring 2012 curriculum is "How does the light get from inside the base to the ends of the fibers [in a fiber optic lamp]?" Children could reasonably answer by identifying setup conditions (a light must be shined at the base of the fibers), identifying activities (the light bounces off of the inside of the fibers), identifying properties of entities (the inside of the fibers act reflectively), and identifying organization of entities (the light starts at the base and reflects back and forth until it reaches the end). While this analysis does not mean that the students cannot use other types of reasoning, it does not make much sense to answer this question by simply stating the target phenomena (the ends of the fibers glow), or simply listing the entities involved. We did not code for chaining or analogy opportunities in this case, as the question did not specifically ask for students to compile information that they learned in any specific activity nor did it specifically ask for students to make an analogy. One example of analogy asked for in the prompts is in an experiment in which children make a rainbow using a spray bottle and a flashlight in the open curriculum. After discussing how the rainbow is made, the prompt asks, "can you explain how rainbows occur in nature?" Here, children are asked to make the analogy between their spray bottle and flashlight experiment and how a rainbow is created in nature. One example of chaining asked for in the prompts is in an experiment in which children bounce a laser off of a mirror and record the incident and reflected angles. The prompt asks children to "write a rule for angle of reflected light." In this case, the children are asked to put together what they learned in the activity to formulate a rule that should hold in the future.

Figure 18 shows the counts of the reasoning opportunities available for students per activity for the activities that they completed. The average counts of reasoning per activity in the guided curriculum is 1.9 $\pm$ .4 and 4.8 $\pm$ .5 counts in the open curriculum, a significant difference of $p < .0001$ (using a T-test).

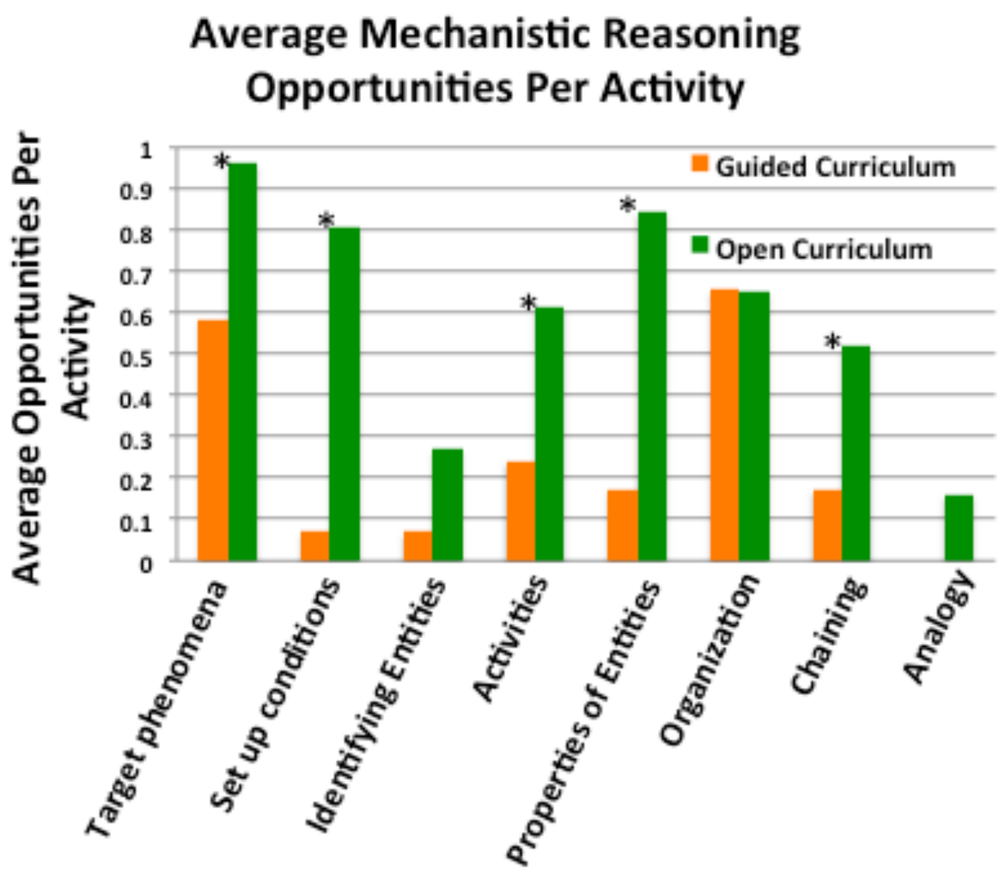


Figure 18: Average reasoning opportunities per activity. Comparison of reasoning opportunities made available in the guided curriculum (Fall 2011) and the more open curriculum (Spring 2012). Contingency table analysis shows a significant difference between curricula, $p < .001$. Stars indicate a significant difference between proportions, $p \leq .01$.

One point to note is that the number of opportunities presented per activity in the open curriculum (4.8 $\pm$ .5 counts per activity) is almost twice as large as the average amount of mechanistic reasoning actually found in the notebooks (2.7 $\pm$ .2 counts per activity). However, we expect the actual counts per activity to be lower than the opportunities per activity. This situation is because we counted all possible opportunities in the ways that the children could have responded to a prompt (that made grammatical sense) - but in responding to a prompt, children do not need to use all opportunities to answer the prompted questions. Also, because children are working in groups with university educators, the children generally talk about the experiment before writing down their final thoughts, doing more mechanistic reasoning in their conversations than actually gets written down in their notebooks. From this analysis, we see that students had more opportunities for reasoning per activity and more opportunities for varied types of reasoning in the open curriculum as compared to the guided curriculum.

To look closer at how students took advantage of opportunities presented to them, we look at three individual activities. The *Rules of Light Bulbs* activity was chosen from the guided curriculum because it required short answers rather than simple yes or no statements. The *Light the Flashlight* activity was the most open inquiry activity in the guided curriculum, coming from the Challenge in Cave 1. The *Hologram Chamber* was the most popular activity in the open curriculum.

The *Rules of Light Bulbs* activity provided opportunities for 3 types of reasoning, and was one of the activities with the most opportunities from this curriculum. However, children exhibited only 2 types of reasoning in their written work (Figure 19). *Light the Flashlight* was the most open activity that was provided in the guided curriculum. Unfortunately, due to its location at the end of the curriculum and the fact that it was an optional challenge, only 4 students completed it. However, as seen in Figure 20, the prompts for this activity provide for 4 types of reasoning and children exhibit 5 types of reasoning in their written work. The *Hologram Chamber* activity (Figure 21) from the open curriculum provided opportunities for 5 types of reasoning, and children exhibited all of these plus an additional 2 reasoning types. We notice a possible trend in which the more open activities generate even more types of reasoning than reasoning opportunities. We believe this is because children are answering their own questions more and answering the prompted questions less in the open curriculum.

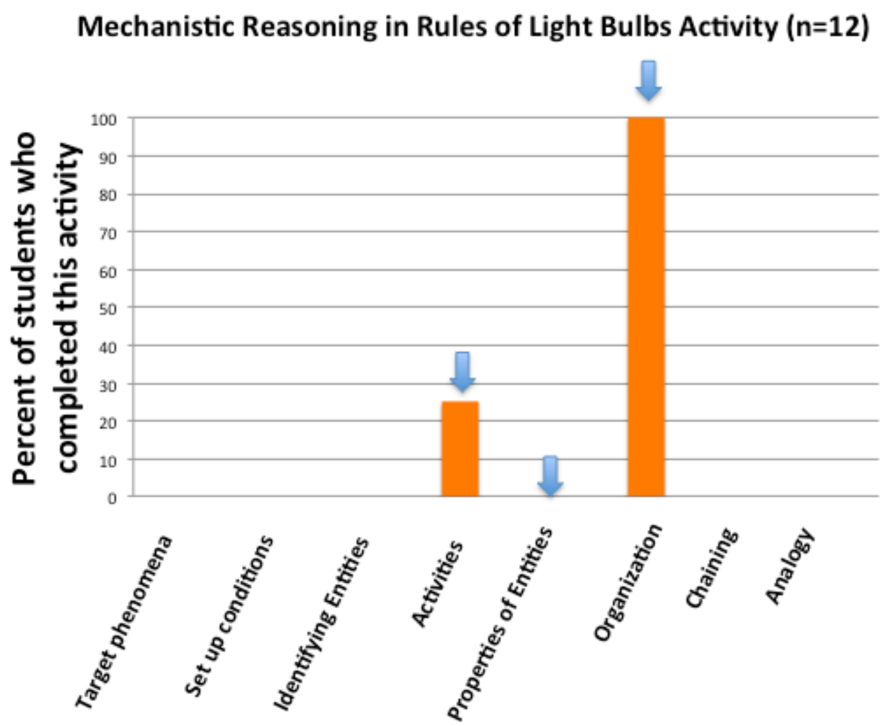


Figure 19: Mechanistic reasoning exhibited in *Rules of Light Bulbs* activity (from guided curriculum). Blue arrows indicate reasoning opportunities. In this activity only two types of reasoning are present; however, the prompt offers opportunities for three types of reasoning.

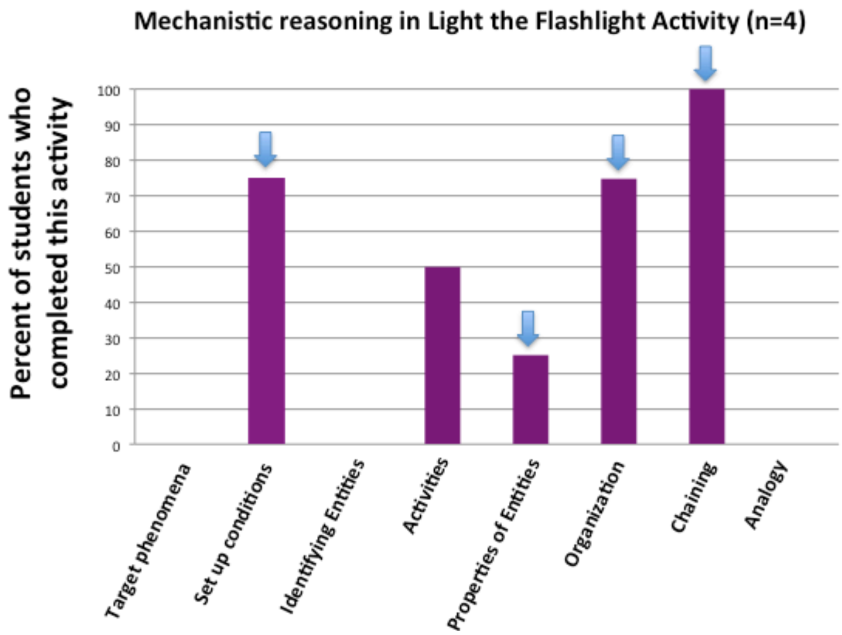


Figure 20: Mechanistic reasoning exhibited in *Light the Flashlight* activity. This activity was one of the most open inquiry activities in the guided curriculum. This figure indicates that the more open prompts even in the circuits curriculum can display a range of mechanistic reasoning types.

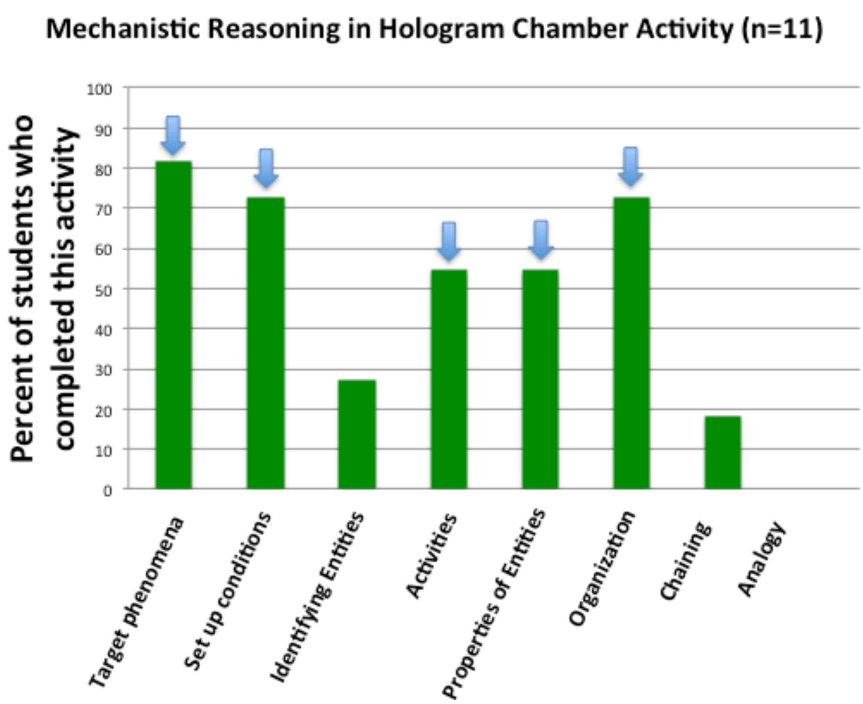


Figure 21: Mechanistic reasoning exhibited in *Hologram Chamber* activity (from the open curriculum). Blue arrows indicate reasoning opportunities. This prompt offers 5 reasoning opportunities and children exhibit 7 different types of reasoning.

We notice that the more open activities, *The Hologram Chamber,* and *Light the Flashlight* offered more varied opportunities for mechanistic reasoning and the children demonstrated more varied types of mechanistic reasoning in the open activities. Furthermore, the varied types of mechanistic reasoning exhibited in the *Light the Flashlight* prompt indicate that an open prompt from the topic of circuits can initiate varied mechanistic reasoning comparable to open prompts from the topic of optics.

8.4 Mechanistic Reasoning in the Fall 2013 Semester of the Open Curriculum

The same open inquiry optics curriculum was run again in the Fall 2013 semester. Using the same analysis methods, we looked at the mechanistic reasoning in the children's notebooks at the same two schools, Laketown Middle School (n =17 children) and Greenwood Middle School (n = 20 children). The children are entirely different from the children who participated in the program in the Spring 2012 semester. Figure 22 shows the breakdown of average mechanistic reasoning per activity in the Fall 2013 semester.

We see a difference in the proportion between the Spring 2012 and Fall 2013 semesters in *Identifying Set Up Conditions*, *Identifying Organization of Entities,* and, *Analogy*. The remaining categories are not significantly different. We expect some differences because all of the children are different, and they may emphasize different types of reasoning in their individual investigations. We also expect to see more attention to *organization of entities* in a circuits curriculum and thus we may see more attention to *organization of entities* in the Spring 2012 semester because the children completed a circuits curriculum in the Fall 2011 semester.

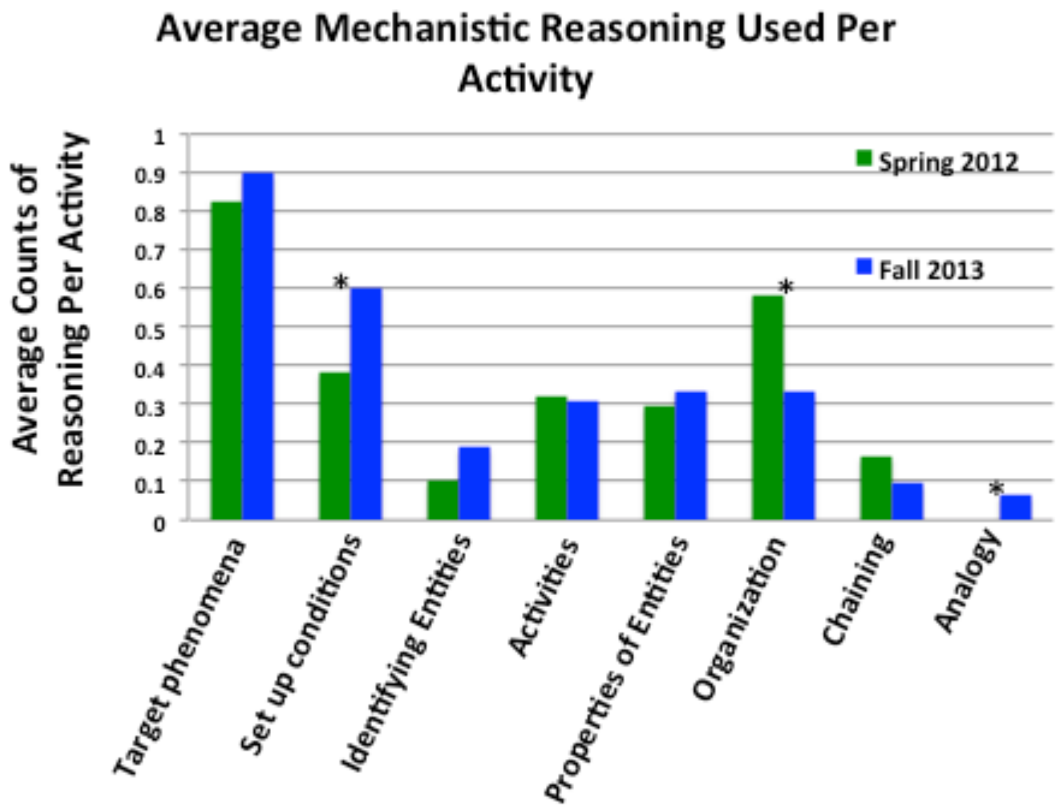


Figure 22: Average amount of mechanistic reasoning per activity. We compare the open inquiry optics curriculum between two semesters at Greenwood Middle School and Laketown Middle School for different children in the program. Stars indicate a significant difference between proportions, $p \leq .01$.

While the amounts of some types of reasoning differ between semesters, we found that on average, the children had $2.8 \pm .2$ codes of reasoning per activity in Fall 2013, which does not differ significantly form $2.7 \pm .2$ codes of reasoning in the Spring of 2012. Thus, the average reasoning per prompt is consistent over two different semesters.

8.5 Discussion

In the more open inquiry activities, we find children are provided with more varied opportunities for mechanistic reasoning compared to guided activities. We also find children actually exhibit more varied written reasoning in their science notebooks with more open inquiry activities compared to the guided activities. We also find that the more open activities provide more reasoning opportunities per activity and that the children actually reason more per activity compared to the guided activities. From analyzing individual prompts, we see that children take up the opportunities provided to them in both curricula but also use more types of reasoning than are presented as opportunities from the prompts in the activities we consider open inquiry. According to Russ et al, the higher ranked types of reasoning have components of the lower ranked reasoning [44]. For example, if a child were to identify the organization of entities, say making a complete circuit, one would expect that the child was doing so by thinking about the entities engaging in activities, say the current flowing through the wires. Thus, the more reasoning codes found in a student's work the more compelling the evidence is that the student is reasoning mechanistically [44]. The more open inquiry curriculum showed evidence of lower ranked codes, higher ranked codes, and a variety of codes in between. The guided curriculum strongly favored describing target phenomena and organization of entities, which could be attributed to the fact that arranging circuits in a way to make the light bulb light requires attention to the organization of entities. Thus we have more evidence of reasoning in the open inquiry curriculum.

As discussed at the beginning of this chapter, mechanistic reasoning is a type of reasoning that values explanations of underlying mechanisms based on observations and not based on textbook correctness. The concept of students being correct because of reasoning rather than textbook correctness is a way in which students can take on the role of the expert rather than thinking of the textbook as the expert. As previously discussed in Chapter 6, according to Hazari et al, encouraging students to take on active expert roles is a practice that is related to positive physics identity development [10].

Furthermore, scientists are focused on learning about the world and use inquiry methods and mechanistic reasoning in building knowledge and understanding. By engaging in these inquiry practices for themselves, students can develop a deep conceptual understanding [45]. Another practice Hazari relates to positive physics identity development is focusing on conceptual understanding of physics [10]. Thus encouraging mechanistic reasoning can positively influence physics identity, and the more open curriculum supports Strand 6 of informal learning environments from Chapter 1.

CHAPTER IX

CONCLUSIONS

9.1 Summary of Findings

We see differences in the opportunities provided by the open and guided curricula and differences in the ways in which the children take up those opportunities. In Chapter 6, we found that children were given more choice in selecting activities to work on in the open curriculum, and different children took up those choices in different ways. We also found that children followed directions from the curriculum less in the open curriculum, preferring to answer their own questions and design their own experiments in about 1/3 of activities. We see this as evidence of children taking on active expert roles in their experience in PISEC.

In Chapter 7, we found that children were writing more and drawing more in the open curriculum. Children also communicated more than they were prompted to in the open curriculum. Thus children are participating, even more than required, in scientific communication. Because communication is valued in PISEC as something that scientists do, children are authoring identities in alignment with what it means to be a scientist in PISEC regarding communication.

In Chapter 8 we found that the open curriculum provides more opportunities for mechanistic reasoning than the guided curriculum. We also found that children use more varied types of mechanistic reasoning, and more mechanistic reasoning per activity in the open curriculum. Mechanistic reasoning values child-centered correctness as opposed to textbook-centered correctness. The children are not told if they are wrong or right but instead are encouraged to come up with their own answers based on their own investigations. Again, we take this as evidence of the children taking on active expert roles in their investigations.

In the open curriculum children are taking on active expert roles in their investigations. Taking on active expert roles in physics has been linked to positive physics identity. Children are also authoring identities in alignment with aspects of being a scientist. Thus, we believe that the open curriculum supports PISEC's goals of promoting children's science identity.

9.2 Implications for Education

The National Research Council and the Next Generation Science Standards both call for some amount of open inquiry in the formal education classroom. However, it is often difficult to fit such explorations into the classroom schedule while also trying to cover the science content required in the standards. PISEC provides an afterschool space for children to participate in open inquiry and practices that are valued in the scientific community that may not be as accessible in formal education. Furthermore, the concept of reflective thought is a scientific practice, and the Next Generation Science Standards call for students to be able to experience more scientific practices in formal education. As discussed in Chapter 2, the process of reflective thought begins with an idea that is personally worthwhile and incorporates a buildup and consummation of anticipation. The promotion of positive physics identity, especially the motivation to learn about the physical world from Strand 1 of informal environments in Chapter 1, can support the beginning of the reflective thought process in science. Thus, PISEC can provide opportunities for open inquiry that are uncommon in formal education and can support children in experiencing scientific practices.

9.3 Future Work

As discussed in previous chapters, children in PISEC communicate and reason more often verbally than they end up writing in their notebooks. Future studies could examine how children exhibit agency, communication, and mechanistic reasoning in their discussions within their groups. Also, the open curriculum relies heavily on the expertise of the university educators working with the children. Future studies could analyze how the university educators interact with children to promote agency, communication, and mechanistic reasoning. Additionally, new curricula in the open curriculum style have been developed (electricity/magnetism, mechanics, sound/fluids/thermo). We now have novel coding schemes to analyze agency, communication, and mechanistic reasoning in children's notebooks. These coding schemes can be used to look at differences between the open curricula to determine what style of open curricula best facilitates PISEC's goals.

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APPENDIX A
GUIDED INQUIRY ACTIVITIES

<u>Cave 1 Activity #1 of 9</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

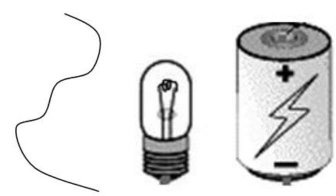
> *<u>**Note to Science Advisor**</u>: Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Full Name____________________________________ Age_______ Date_______________

You are in a dark cave. To figure out how to light the bulb, first, you have to figure out what you already know!

*Draw <u>**one wire**</u>, one light bulb, and one battery that will light the bulb as shown here.*

Do not cut the wire.

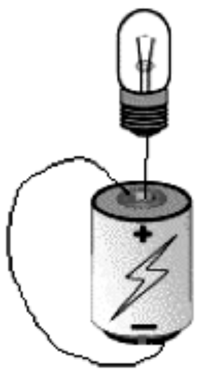


<u>Cave 1 Activity #2 of 9</u>

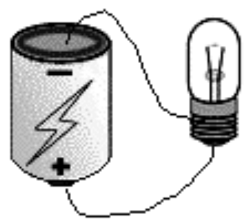
<u>Do not work with anyone else.</u> **_Science Advisor Init.______ _**

***<u>Note to Science Advisor</u>**: Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

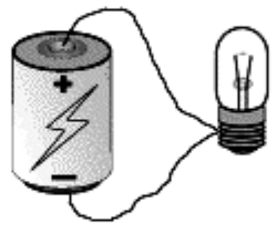
For each circuit, will the bulb light? (Circle your answer.)



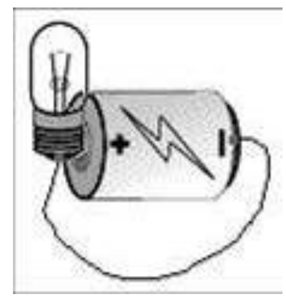
YES NO



YES NO

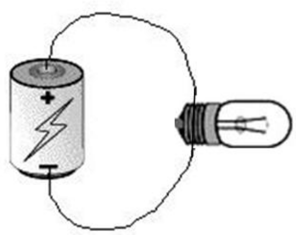


YES NO



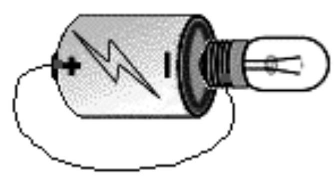
YES NO

YES NO



YES NO

YES NO



YES NO

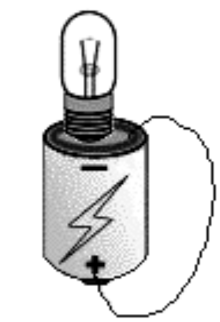
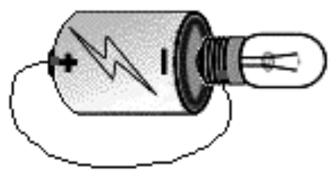
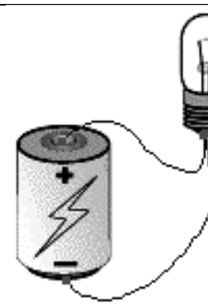
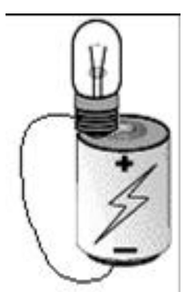
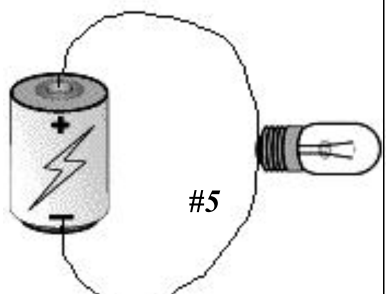
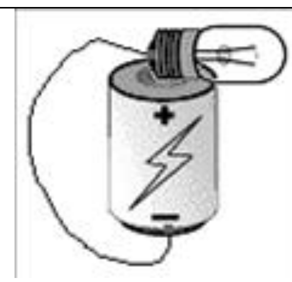
Cave 1 Activity #3 of 9

Do not work with anyone else. ***Science Advisor Init.______***

> ***Note to Science Advisor***: *Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Your team is counting on you to figure out how to light the bulb to explore caves. To figure it out, you need to understand what you think before hand.

*Will these bulbs light? For each circuit write **YES** or **NO** next to the word **PREDICTION**.*

 ***#1*** ***Prediction:___________***	 ***#2*** ***Prediction:___________***	 ***#3*** ***Prediction:___________***
 ***#4*** ***Prediction:___________***	 ***#5*** ***Prediction:___________***	 ***#6*** ***Prediction:___________***

<u>Cave 1 Activity #4 of 9</u>

<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

<u>Note to Science Advisor</u>*: Make sure the person understands the question. Do not help them with the answer, but guide them to understand what they think. We are looking for 2 to 3 rules here.*

For each circuit, what rules did you use to decide which bulbs light? Do not change your predictions in the previous activity. Just write your reasons here.

Circuit #	*Lights?*	*Why?*
1		
2		
3		
4		
5		
6		

Cave 1 Activity #5 of 9
Work with a group. ***Science Advisor Init.______***

Note to Science Advisor*: Make sure the group understands the question. Do not help them with the answer, but guide them to understand what they think. Act as facilitator. Do not let them change their answers above.* **The group must write something here to get initials.**

Group members:____

For each circuit, talk about whether the bulb lights and why.

What do you think now?

Write your **changes** here.

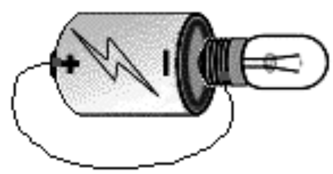
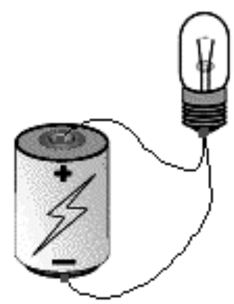
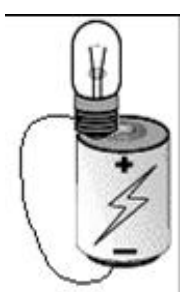
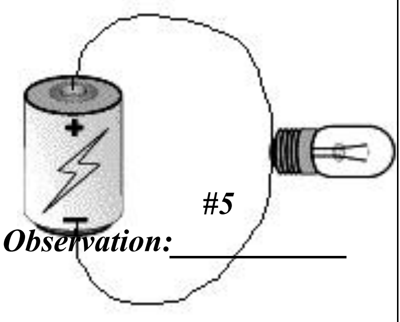
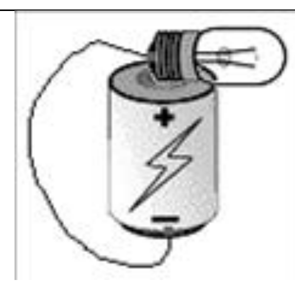
Cave 1 Activity #6 of 9
Do not work with anyone else. ***Science Advisor Init.______***

> ***Note to Science Advisor***: *Let them explore this until they are done. Use guiding questions to lead them eventually to the correct conclusions. Show them how to use the Playdoh to hold the battery.*

Try the experiment! Now that you understand what you think, you can compare your ideas to what lights the bulb.

You will need: One loose battery, one loose bulb, two bare copper wires, Playdoh.

*Does the bulb light? Write **YES** or **NO** next to the word: **OBSERVATION**.*

 ***#1*** ***Observation:___________***	 ***#2*** ***Observation:___________***	 ***#3*** ***Observation:___________***
 ***#4*** ***Observation:___________***	 ***#5*** ***Observation:___________***	 ***#6*** ***Observation:___________***

Cave 1 Activity #7 of 9
Do not work with anyone else. **_Science Advisor Init.______**

Note to Science Advisor: *Use guiding questions to make sure they draw correct conclusions.*

For each circuit, what do you think the rules are now? Do not change your answers. What do you think now? Write your ***changes*** *here.*

Circuit #	*Lights?*	*Why?*
1		
2		
3		
4		
5		
6		

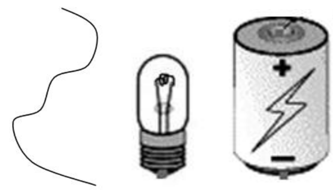
Those caves are going to be really cool to explore!

Cave 1 Activity #8 of 9
Do not work with anyone else. **Science Advisor Init.______**

> ***Note to Science Advisor***: *Make sure the person understands the question, but do not help with the answer. Make sure the answer is not ambiguous.*

Draw **one wire**, *one light bulb, and one battery that will light the bulb as shown here.*

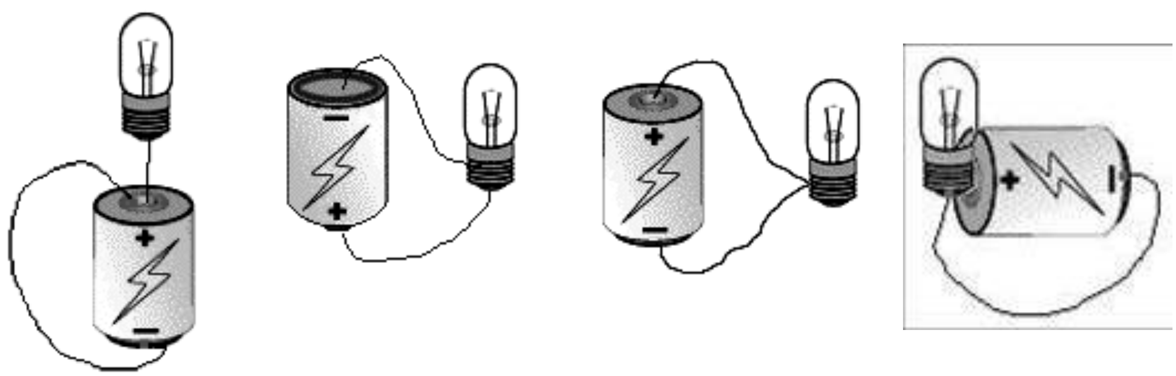
Do not cut the wire.



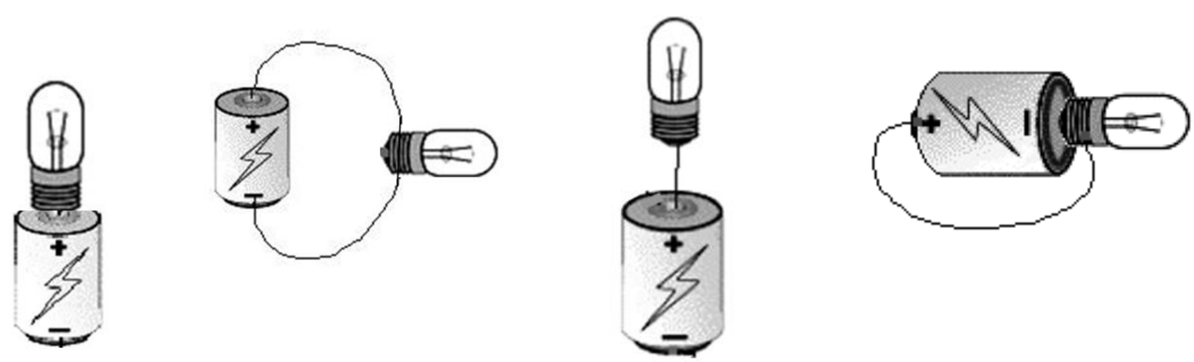
Cave 1 Activity #9 of 9
Do not work with anyone else. **Science Advisor Init.______**

> ***Note to Science Advisor***: *Make sure the person understands the question, but do not help with the answer.*

For each circuit, will the bulb light? (Circle your answer.)



YES NO YES NO YES NO YES NO



YES NO YES NO YES NO YES NO

Cave 2 Activity #1 of 6
Do not work with anyone else. ***Science Advisor Init.______***

Note to Science Advisor: *Make sure the person understands the question, but do not help with the answer.*

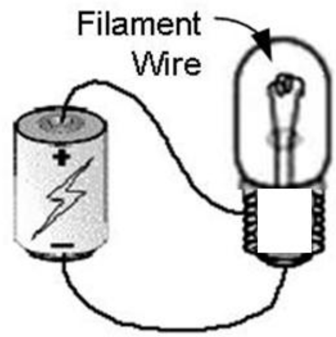
Full Name____________________________________ Age_______ Date_______________

Draw lines to connect:

the two filament support wires

to the two wires from the battery.

(Ask for help!!)

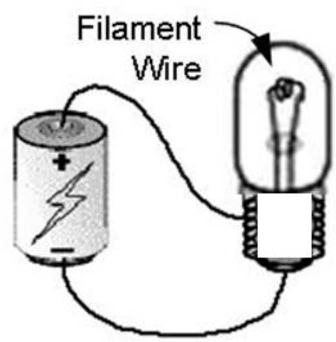


Cave 2 Activity #2 of 6
Do not work with anyone else. ***Science Advisor Init.______***

Note to Science Advisor: *Use guiding questions to make sure they draw correct conclusions.*

See for yourself! Ask your instructor to show you the ***picture of the cut-apart bulb****.*

Show *how the two filament support wires are connected to the two wires from the battery.*



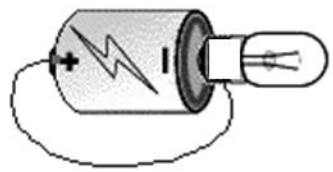
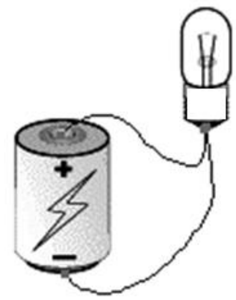
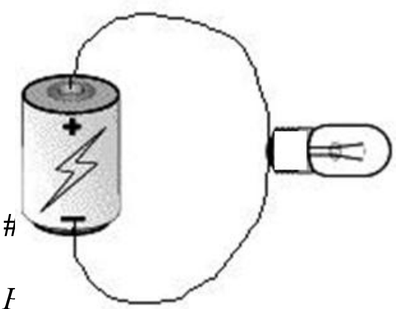
Cave 2 Activity #3 of 6

Do not work with anyone else. **_Science Advisor Init.______**

> ***Note to Science Advisor***: *Use guiding questions to make sure they draw correct conclusions. This part must be drawn very clearly.*

For each circuit, ***draw the connection*** *inside the bulb.*

Will the bulb light? Write ***YES*** *or* ***NO*** *next to the word* ***PREDICTION****.*

 ***#1*** Prediction______________	 ***#2*** Prediction______________	 ***#3*** Prediction______________
 ***#4*** *Prediction*______________	 # *I*	 ***#6*** Prediction______________

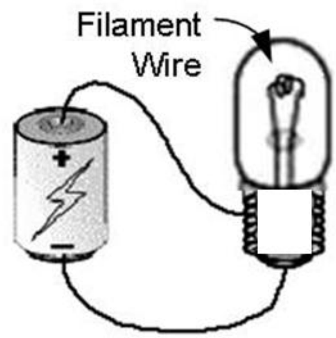
<u>Cave 2 Activity #4 of 6</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

<u>Note to Science Advisor</u>*: Make sure the person understands the question, but do not help with the answer.*

Draw lines to connect:

the two filament support wires

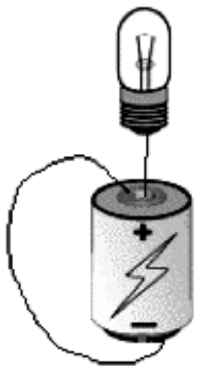
to the two wires from the battery.



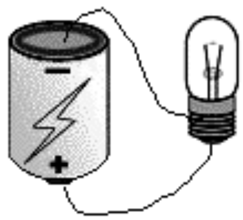
Cave 2 Activity #5 of 6
Do not work with anyone else. **_Science Advisor Init.______**

Note to Science Advisor: *Make sure the person understands the question, but do not help with the answer.*

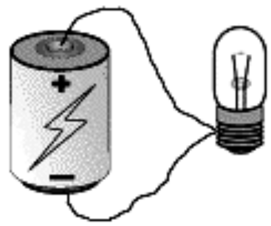
For each circuit, will the bulb light? (Circle your answer.)



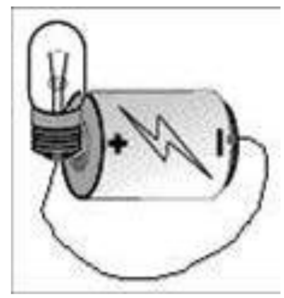
YES NO



YES NO

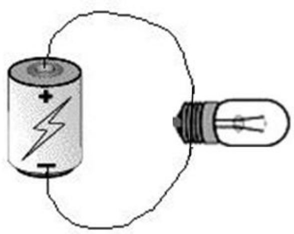


YES NO



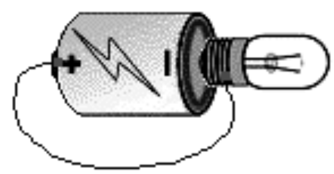
YES NO

YES NO



YES NO

YES NO



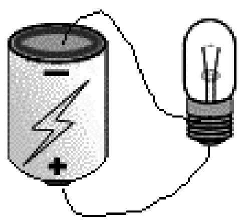
YES NO

FELLOW INITIALS_________________

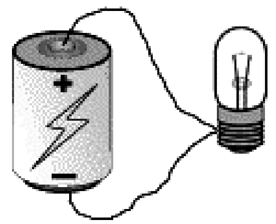
<u>Cave 2 Activity #6 of 6</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

<u>Note to Science Advisor</u>*: Make sure the person understands the question, but do not help with the answer.*

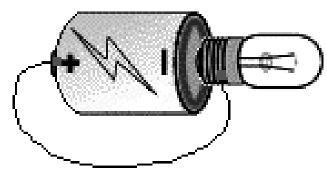
For each circuit, will the bulb light? (Circle your answer.)



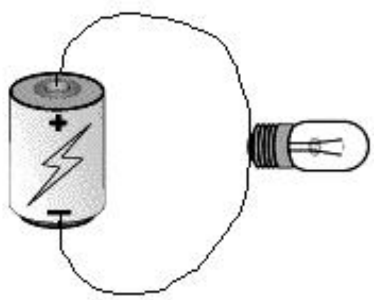
YES ***NO***



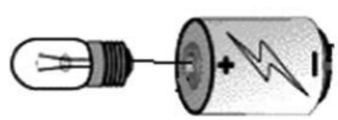
YES ***NO***



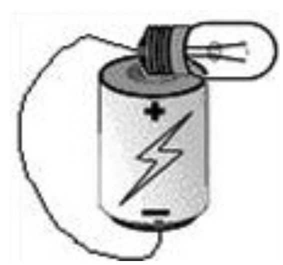
YES ***NO***



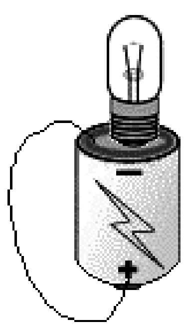
YES ***NO***



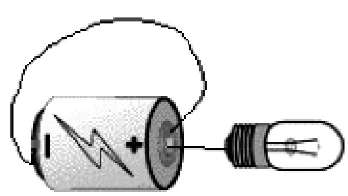
YES ***NO***



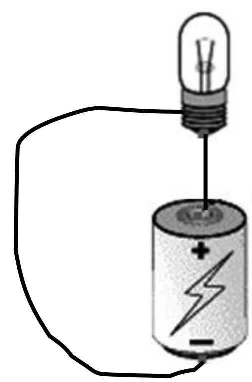
YES ***NO***



YES ***NO***



YES ***NO***



YES ***NO***

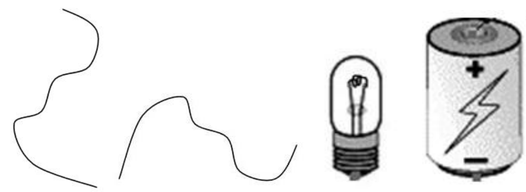
Cave 3 Activity #1 of 9
Do not work with anyone else. **Science Advisor Init.______**

Note to Science Advisor*: Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Full Name___________________________________ Age_______ Date_______________

Draw **two wires***, one light bulb, and one battery that will light the bulb as shown here.*

Use both wires.

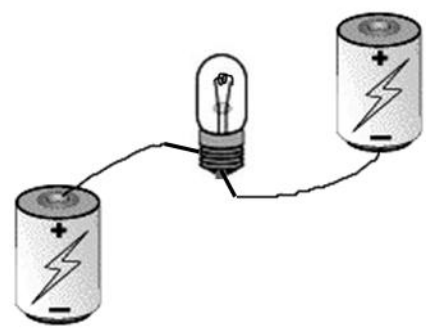


Cave 3 Activity #2 of 9
Do not work with anyone else. **Science Advisor Init.______**

Note to Science Advisor*: Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Do you think the light bulb will light?

Why or why not?

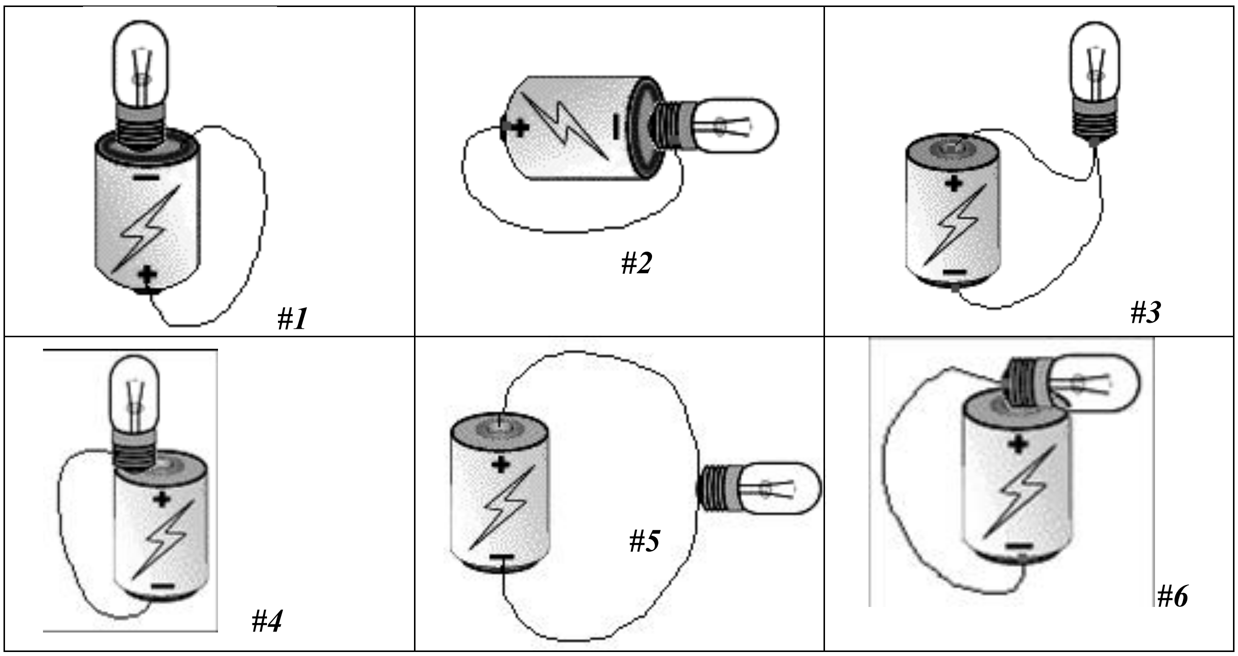


Cave 3 Activity #3 of 9
Do not work with anyone else. **Science Advisor Init.______**

Note to Science Advisor: *Use guiding questions to make sure they draw correct conclusions.*

Which of the setups use a battery, bulb and a ***single*** *wire and the bulb lights?*

Circle the setups you chose.



Cave 3 Activity #4 of 9
Do not work with anyone else. **Science Advisor Init.______**

Note to Science Advisor: *Use guiding questions to make sure they draw correct conclusions.*

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.

<u>Cave 3 Activity #5 of 9</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

> ***<u>Note to Science Advisor</u>****: Use guiding questions to make sure they draw correct conclusions.*

Figure out an arrangement using the battery, bulb and <u>two</u> wires that light the bulb.

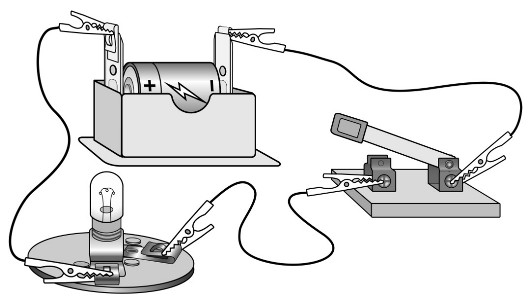
Draw the circuit below.

<u>Cave 3 Activity #6 of 9</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

> ***<u>Note to Science Advisor</u>****: Use guiding questions to make sure they hook up the circuit correctly. This is the first time they are using holders for batteries and bulbs. Make sure they notice that the bulb holder touches side and bottom.*

Hook up this circuit.

You will need:
Switch,
Bulb & holder,
Battery & holder,
3 hook-up wires.

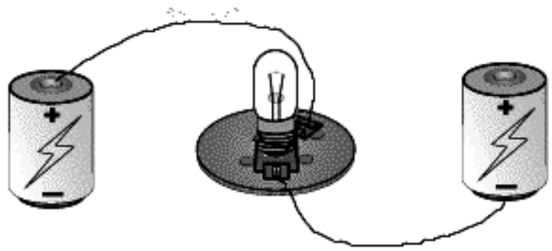


Cave 3 Activity #7 of 9
Do not work with anyone else. ***Science Advisor Init.______***

Note to Science Advisor*: Use guiding questions to make sure they hook up the circuit correctly.*

Hook up this circuit.

You will need:
Switch,
Bulb & holder,
2 Batteries & 2 holders,
2 hook-up wires.



Question 1: Does the bulb light?

Question 2: Does the bulb need to be connected to two ends of the same battery to light?

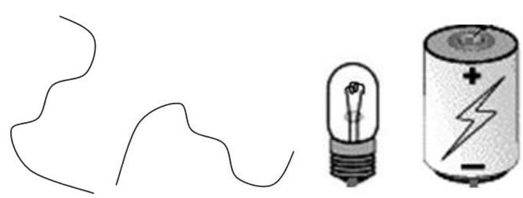
Question 3: How do you know?

Cave 3 Activity #8 of 9
Do not work with anyone else. ***Science Advisor Init.______***

Note to Science Advisor*: Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Draw **two wires***, one light bulb, and one battery that will light the bulb as shown here.*

Use both wires.

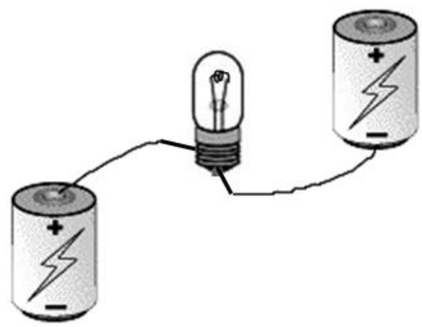


<u>Cave 3 Activity #9 of 9</u>
<u>Do not work with anyone else.</u> ***Science Advisor Init.______***

<u>Note to Science Advisor</u>: *Make sure the person understands the question, but do not help with the answer. Make sure answer is not ambiguous.*

Do you think the light bulb will light?

Why or why not?



FELLOW INITIALS___________________

Cave 1 Challenge #1 of 4 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

At your feet you find a flashlight. Look carefully at this flashlight. Make a careful drawing of what it looks like inside.

Cave 1 Challenge #2 of 4 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

Make a drawing of the flashlight showing the ***<u>circuit</u>****. You must draw how the bulb is connected to the battery.*

How many wires are used to make this circuit?

Cave 1 Challenge #3 of 4 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

> ***<u>Note to Science Advisor</u>****: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

If you were going to use a battery, bulb, and wires, how would you make this circuit? You can use a battery, bulb, and wires to find out. Draw the circuit here.

Cave 1 Challenge #4 of 4 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

> ***<u>Note to Science Advisor</u>****: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

In the flashlight, does it matter which way you put the batteries in? Why or why not?

In the circuit version you drew in Cave 1 Challenge #3, does it matter if you switch the battery so that the negative end is where you drew the positive end? Why or why not?

Cave 2 Challenge #1 of 3 **Science Advisor Init.______**

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

On the ground these appear: one battery, one bulb, one battery holder, one light bulb holder, and a few wires. Make a circuit to light the bulb with these items. Draw the circuit.

Cave 2 Challenge #2 of 3 **Science Advisor Init.______**

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

Suddenly these items appear!

copper	*paper*	*iron or steel*	*porcelain*	*plastic*
glass	*aluminum*	*rubber*	*pencil lead*	

Insert each object one by one into the circuit. Find which objects will let the bulb glow brightly, dimly, or not at all:

*Glows brightly*____

*Glows dimly*____

*Goes out*____

Cave 2 Challenge #3 of 3 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

What do the objects that let the bulb light have in common? Explain.

Cave 3 Challenge #1 of 4 ***Science Advisor Init.______***

<u>You may work alone or in a group</u>

<u>Note to Science Advisor</u>*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

You find one battery, one battery holder, one bulb, one socket, a few wires, and one switch. Make a circuit that lights the bulb using all of these objects. Draw the circuit.

Cave 3 Challenge #2 of 4 ***Science Advisor Init.______***

You may work alone or in a group

Note to Science Advisor*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

A message appears on the wall. It says, "When the switch is open, the circuit is not complete. It is an ***open circuit****."*

Add one more switch to the circuit. This switch and the bulb should form a ***closed loop****. Open and close the switch to test that it works.*

WIZARD WARNING: The Wizard commands you to not leave the switch closed for long!!! (It ruins the battery and you will be lost in the dark cave.)

Draw the circuit.

Cave 3 Challenge #3 of 4 ***Science Advisor Init.______***

You may work alone or in a group

Note to Science Advisor*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

Explain what happens to the bulb when this extra switch is closed.

Cave 3 Challenge #4 of 4 ***Science Advisor Init.______***

You may work alone or in a group

Note to Science Advisor*: Make sure the person or group understands the challenge. Act as facilitator. Use guiding questions to lead them eventually to the correct conclusions.*

Another message appears on the wall. It says, "You have successfully conquered Challenge 3! By closing the switch you have created a ***short circuit****. The bulb is* ***shorted out****."*

APPENDIX B

OPEN CURRICULUM ACTIVITIES

Rainbow Room: Level 1

In this experiment you are going to shine a flashlight through a special piece of glass called a prism.

1. Discuss with your group what you think will happen?
2. Now do it! **Draw a color picture of your experiment.**
3. **Write: What is important about the position of the prism and the flashlight?**
4. The color of the light from the flashlight is "white" until you shine it through the prism. **Write: What is the prism doing to the light?**

Science Advisor Initials _______

In this experiment you are going to use a "rainbow peephole" to look at the lights in the room.

1. Discuss with your group what you think you will see?
2. Now do it! **Draw a color picture of what you see.** What is different from your prediction?
3. What will happen if you rotate the peephole?
4. Rotate the peephole! **Write down what happens.**
5. What do you think the peephole is made out of?

Science Advisor Initials _______

Make a rainbow with sunlight and a spray bottle of water. If it is not a sunny day or you can't go outside, skip this one or use another light source in the room but BE CAREFUL ABOUT GETTING ANYTHING ELECTRICAL OR IMPORTANT WET.

1. **Draw a picture of your experiment and label it.**
2. What happens when the light hits the water?
3. Can you explain how rainbows occur in nature?
4. **Write down what your group talked about.**

Science Advisor Initials _______

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Rainbow Room: Level 2

Hold colored cellophane over mini flashlights to make new colors of light. You might want to double up on the cellophane. Try lots of combinations.

1. Make orange light! How did you make it?
2. Make at least 2 more colors.
3. **Write all your combinations in a table.**
4. Discuss in your group: How could you make white light from colored light? **Write down your ideas.**
5. Hold the the cellophane up to your eye. What do you see?

Science Advisor Initials _______

Open the PhET simulation, ***Color Vision***, on the computer.

1. Play with the simulation for 5 minutes. Time yourself with the stopwatch! (If you want to add 2 more minutes, do it!)
2. Discuss with your group how you think you could make white light.
3. Now do it! Make white light.
4. **Write how you made white light.**
5. Discuss with your group what white light is made of?

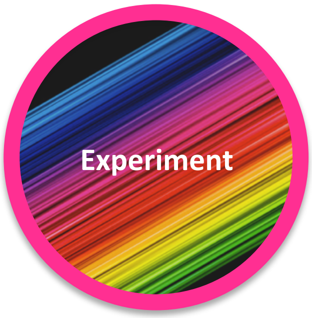
Science Advisor Initials _______

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Rainbow Room: Level 3



In this experiment, you will use the spectroscope to look at an incandescent light bulb. BE CAREFUL – THE BULB GETS HOT! Turn off the light. Then use a towel to unscrew the bulb.

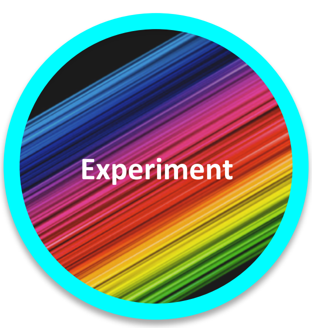
1. What color is the light from the bulb that you see without the spectroscope?
2. **Draw a color picture of what you see with the spectroscope. Make sure you include the numbers in your picture.**
3. What do you think the spectroscope does to the light?

Science Advisor Initials _______

In this experiment, you will use the spectroscope to look at red and green colored light bulbs. BE CAREFUL – THE BULBS GET HOT! Turn off the light. Then use a towel to unscrew the bulb.

1. What color is the light from the bulb that you see without the spectroscope?
2. **Draw a color picture of what you see. Make sure you include the numbers in your picture.**
3. How do you think they make colored light bulbs?

Science Advisor Initials _______



In this experiment you will use the spectroscope to look at the two fluorescent light bulbs (white and black). BE CAREFUL – THE BULB GETS HOT! Turn off the light. Then use a towel to unscrew the bulb.

1. What color is the light from the bulb that you see without the spectroscope?
2. **Draw a color picture of what you see. Make sure you include the numbers in your picture.**
3. What is the difference between the two light bulbs?

Science Advisor Initials _______

Challenge

Do all the experiments first! When you have completed the experiments, discuss these questions:

1. The color pictures you drew for each bulb is called a spectrum. **Write: Why do different bulbs have a different spectrum?**
2. How are the numbers related to the colors? What do you think the numbers mean?
3. **Write what your group talked about.**
4. Are there any other lights in the room you can look at with the spectroscope? Can you identify them?

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Image Room: Level 1

Experiment

Examine a lens.

1. What do you see when looking through it?
2. What do you think would happen if you move the lens farther away or closer to your face?
3. Do the experiment! What do you see? Try looking at something written or typed. **Write what happens.**
4. **Write: How do you think glasses work to help people see?**

Science Advisor Initials _______

Experiment

In this experiment you will look through a pinhole.

1. What do you see when you look through it? Are objects clear or blurry?
2. Discuss with your group: What do you think it means for an image to be "in focus"? **Write a definition.**
3. Why do you think your pupils (the black part of your eye) get bigger in the dark and smaller in bright light? Try this experiment if you haven't done it before!

Science Advisor Initials _______

Challenge

Take several photographs of the classroom with a computer and webcam.

1. Which objects are clear and which ones are blurry?
2. Discuss with your group what it means for an object to be "clear" or "blurry". **Write definitions.**
3. Discuss: why are some objects clear and some blurry?
4. The webcam has a lens in it. Discuss how a camera is like your eye. **Write your ideas.**

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Image Room: Level 2

Experiment

In this experiment use the magnifying glass to look at various objects.

1. Find 3 different objects. Predict what the objects will look like with the magnifying glass.
2. Do the experiment! **Draw two pictures of each object: what it looks like with your eye and what it looks like in the magnifying glass.**
3. How does what you see compare with your prediction?
4. **Write: How does the magnifying glass work?**

Science Advisor Initials _______

Experiment

In this experiment use the microscope to look at the wizard picture and at least 1 other object.

1. Predict what the objects will look like with the microscope.
2. Do the experiment! **Draw two pictures: what the objects look like with your eye and what it looks like in the microscope.**
3. What are the differences between your pictures?
4. Discuss: Why are the images are upside down?

Science Advisor Initials _______

Challenge

Open the PhET simulation, ***Geometric Optics***, on the computer.

1. Play with the simulation for 5 minutes – time yourself with the stopwatch! (Add 3 more minutes if you want!)
2. What do you think the lines represent?
3. In the simulation, which thing is the object and which thing is the image of the object?
4. **Write: How can you make the biggest image possible?**
5. Discuss: Why do you think the image is upside down?

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Image Room: Level 3

Experiment

Make an image on the screen with one of the lenses using the light and the rail.

1. **Draw a picture of your setup and label the parts.**
2. **Write: How do you know when you have made an image?**
3. How far away is the light from the lens? How far away is the lens from the image? **Record your data.**
4. Switch lenses! **Measure the same distances.**
5. What is different about the lenses? **Write three pieces of evidence.**

Science Advisor Initials ________

Experiment

In this experiment you will make big and small images with just one lens using the light and the rail.

1. What do you think will be the difference in your setup between the big image and the small image?
2. Do the experiment! Make at least 2 images**. Measure the sizes of the images. Record the data!**
3. **At the same time, measure the distance from the lens to the image and the light to the lens.**
4. Compare your measurements and your predictions.

Science Advisor Initials ________

Challenge

Make an image on the screen with two lenses using the light and the rail.

1. **Draw a picture of your setup.**
2. **Write about how to make an upside down image. Then describe how to make the image right-side up.**

Science Advisor Initials ________

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations!

Science Advisor Initials ________

Bending Room: Level 1

Experiment

In this experiment you will place a pen in a cup of water.

1. What does the object look like in the air? **Draw a picture.**
2. Do the experiment! Put the pen in the water. **Draw a picture of what you see.**
3. **Write: What is the difference between your two pictures?**
4. Put another object in the water. How does it look?

Science Advisor Initials _______

Challenge

In this experiment you will shine a laser on the bottom surface of a CD.

1. First look at the CD when you hold it up to the room lights. **Draw a picture of what you see.**
2. What do you think will happen if you shine the laser on the CD?
3. Do the experiment! **Draw a picture of what you see.**
4. How many laser beams come out of the CD?

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Bending Room: Level 2

Experiment

STOP! DO THE LASER SAFETY BADGE FIRST! Then, shine the laser at the wall or piece of paper through the half circle plastic container.

1. Where does the laser beam hit the wall when the container is empty?
2. Now fill the container with water. Shine the laser straight through the container. Where does the laser hit on the other side?
3. Twist the container. What happens to the laser beam?
4. **Draw a picture of your setup. Label the laser beam.**
5. **Write: What does the water do to the laser beam?**

Science Advisor Initials ________

Challenge

Open the PhET simulation, ***Bending Light.***

1. Play with the simulation for 5 minutes. Time yourself with the stopwatch! (You can have 3 extra minutes if you want!)
2. Make a rainbow!
3. Can you make a rainbow then make white light again?
4. **Write: What happens to the speed of the light when it goes into a new material?**
5. **Write a rule for speed and bending of light.**

Science Advisor Initials ________

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials ________

Bending Room: Level 3

Challenge

Open another PhET simulation: **"Lasers"**.

1. Play with the simulation for 5 minutes. Time yourself with the stopwatch! (You can have 3 extra minutes if you want!)
2. **Write 2 cool thing you did with the simulation.**

Science Advisor Initials _______

Challenge

Open another PhET simulation: **"Wave Interference"**.

1. Play with the simulation for 5 minutes. Time yourself with the stopwatch! (You can have 3 extra minutes if you want!)
2. **Write 2 cool thing you did with the simulation.**

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Reflections Room: Level 1

Experiment

Examine two mirrors.

1. Use one mirror and hold it so you can see other parts of the room without turning around. **Write: How does a mirror work?**
2. Hold two mirrors at a right angle to each other in front of your nose. **Write: How many images of yourself do you see?**

Science Advisor Initials _______

Experiment

In this experiment, you are going to put on special sunglasses.

1. Discuss: What do you think you will see?
2. Put them on! Can you see behind you without turning around?
3. **Write: How do these special sunglasses work?**
4. How would you make your own pair?

Science Advisor Initials _______

Experiment

Examine the the 3D Hologram chamber. Be careful not to leave fingerprints on the inside of the chamber!

1. Put in at least 2 different objects: try something shiny, clear or solid. **Write down what you see!**
2. Discuss: How do you think the chamber works?
3. Look at the diagram of the chamber. Discuss what it means with your group.
4. Try this! Take the bottom half of the chamber and move it from far away to close to your face. **Write: What happens to your reflection?**

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Reflections Room: Level 2

Challenge

STOP! Do the laser safety badge first! Then, set up a series of at least 3 mirrors and a laser pointer in playdoh.

1. Make the laser beam go in a circle using the mirrors.
2. **Draw your set up. Track the beam with a post-it note. Label the beam with arrows to show its direction.**
3. **Write: Why does light reflect off of a mirror? What will light not reflect off of? Why?**

Science Advisor Initials _______

Experiment

Examine the fiber optic lamp.

1. **Write: How does the light get from inside the base to the ends of the fibers? What does this have to do with reflections?**
2. **Draw a picture of how you think the light gets from the base to the ends of the fibers.**
3. Guess how many fibers there are! **Write it down!**

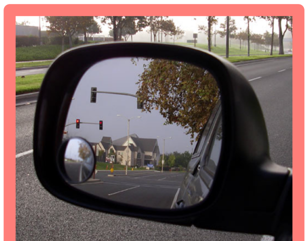
Science Advisor Initials _______

Experiment

STOP! Do the laser safety badge first! Then, on top of your notebook, set up one mirror and a laser pointer in playdoh. Bounce the laser off the mirror and make it hit the target!

1. **Draw your set up. Track the beam with a post-it note. Mark on your notebook where the beam goes. Use arrows to show the beam path.**
2. Use a protractor to measure the angle that the light hits the mirror and the angle the light bounces off of the mirror. **Record your results.**
3. **Write a rule for angles of reflected light!**

Science Advisor Initials _______



Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

Reflections Room: Level 3

Challenge

Play Khet 2.0 with at least one other person! Once you have played for 20 minutes or one entire game you must move to a different room OR do a Big Idea!

1. **Write three rules of the game.**
2. **Write: Describe a good strategy to use in order to win.**

Science Advisor Initials _______

Big Idea!

Design your own experiment!

Create a plan, make a prediction, make measurements, and record your observations! Write down everything for the Wizard!

Science Advisor Initials _______

APPENDIX C
STATISTICS USED FOR THIS THESIS

1. Difference between proportions for a Binomial Distribution [41]

   In many of the coding schemes in this thesis, a given code could only be counted once per activity. This gives a binomial distribution, with a 1 meaning the code is present and a 0 meaning the code is not present. In many cases we compare differences between proportions.

   To do this we find the standard deviation of the distribution of differences between sample proportions σDDSP.

   $$\sigma\text{DDSP} = \sqrt{\frac{p_a(1-p_a)}{n} + \frac{p_b(1-p_b)}{m}}$$

   Where p_a is the proportion of 1s in sample a, p_b is the proportion of 1s in sample b, n is the size of sample a, and m is the size of sample b.

   When you include $\pm$ 2.576σ from the mean, you capture 99% of the normal distribution. So σDDSP multiplied by 2.576 will give a 99% confidence interval for the difference between proportions ($p \leq .01$).

   Thus we look at (pa-pb) $\pm$ 2.576σ. If 0 lies in between the lower and upper limits, than there is no statistical difference in proportions. If 0 is not in between the limits than there is a statistical difference in proportions ($p \leq .01$).

2. T-Test [41]

   In some of the statistics in this thesis we were able to calculate an average and a standard deviation for normal distribution. We then tested the difference between the means.

   First we calculated a t-score using the following equation:

   $$t = \frac{\bar{x}_a - \bar{x}_b}{\sqrt{\frac{\Sigma(\bar{x}_a - x_a)^2 + \Sigma(\bar{x}_b - x_b)^2}{n_a + n_b - 2}\left(\frac{1}{n_a} + \frac{1}{n_b}\right)}}$$

   Then, we looked up the critical value of in a critical value of the t-distribution table (we used table 3 from "Statistics at your Fingertips" [41]). We used $n_a + n_b - 2$ as the degrees of freedom.

   If t is larger than the critical value for the specific degrees of freedom and the desired confidence interval, then the difference between the means in significant.

3. Contingency Table analysis [41]

In some cases we wanted to compare overall populations with independent categories. For this case we used a contingency table analysis.

The question is if there is a significant difference between the two overall populations.

For example we wanted to compare counts of mechanistic reasoning between the two curricula. We set up our contingency table the following way (we had 8 categories in our actual analysis):

	Guided	Open	Totals
Category 1 (C1)	Total counts in category 1 guided	Total counts in category 1 open	Row total C1
Category 2 (C2)	Total counts in category 2 guided	Total counts in category 2 open	Row total C2
Category 3 (C3)	Total counts in category 3 guided	Total counts in category 3 open	Row total C3
Totals	Column total guided	Column total open	Total

If there is no significant difference between populations than we would expect the same proportions in each category. Thus we can set up a table of expectations if there is no difference in proportions.

Expectations	Guided	Open
Category 1	$\frac{(Row\ total\ C1)(Column\ total\ guide}{Total}$	$\frac{(Row\ total\ C1)(Column\ total\ oper}{Total}$
Category 2	$\frac{(Row\ total\ C2)(Column\ total\ guide}{Total}$	$\frac{(Row\ total\ C2)(Column\ total\ oper}{Total}$
Category 2	$\frac{(Row\ total\ C3)(Column\ total\ guide}{Total}$	$\frac{(Row\ total\ C3)(Column\ total\ oper}{Total}$

Finally we just do a chi-square test for significant difference between observed (O) and expected (E).

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i}$$

Using (# of rows -1)(# of columns -1) as the degree of freedom, we then looked in Table 4 of "Statistics at your Fingertips" [41] for Critical values of the Chi-Square Distribution. Given the specific degree of freedom, and the specific confidence interval, if the Chi-Square value you calculated is greater than the critical value there is a significant difference in populations.