TINKERING TOWARDS THEORIES: THE ROLE OF TINKERING IN BUILDING SCIENTIFIC MODELS

by

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DEDICATION

I dedicate this thesis to my mother and grandmother who have unconditionally supported me throughout my educational journey. Their encouragement allowed me to pursue my dreams, educational and otherwise, and helped me persist during trying times. I eternally appreciate their love and support, and hope they know how pivotal they are to my success now and in the future. I would also like to dedicate this thesis to all the women who showed me that it is possible to be a scientist, researcher, teacher, and lifelong learner. These women continue to inspire and motivate me for the future.

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ABSTRACT

Tinkering and modeling have increasingly gained traction within science education. For this study, I adopt the construct of tinkering, which is usually applied to the development of tangible artifacts and consider how this activity might apply to the development of novel models and theoretical objects in science. Data was collected from student artifacts and coding of transcripts was performed to identify how students design models in science, with a focus on how students engage in tinkering when doing so. Using a multiple case study approach, I examined two cases of undergraduate pre-service science teachers' development of models of light and color. The data shows that students can invent theoretical objects to productively model complex abstract scientific ideas. Examining these models revealed that students use many of the same tinkering processes- iteration, improvisation, playfulness, and shifting of emergent goals- as seen in tinkering in engineering, but students use theoretical objects (ideas) instead of tangible objects. Coding of student discussion further showed that students can tinker with theoretical objects in an iterative, playful, improvisational manner with shifting goals to refine and improve their models. Overall, including tinkering and modeling in the science classrooms creates a space where students can richly develop scientific ideas and novel models of scientific phenomena.

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LIST OF ABBREVIATIONS

BSU	Boise State University
NGSS	Next Generation Science Standards
STEM	Science, Technology, Engineering, and Mathematics
STEM-ED	Science, Technology, Engineering, and Mathematics Education

CHAPTER ONE: INTRODUCTION

In this study, I explore the intersection of model building and tinkering in the science classroom. I examine how a proposed activity of "idea tinkering" could lend itself to aiding students in the development of coherent mechanistic models of scientific phenomena. This chapter begins by breaking down the two main constructs of this study: modeling and tinkering. In this chapter, I explain why modeling and tinkering matter for this study and for the science classroom. Then, I delve more deeply into the purpose of this thesis and supply the research questions that will guide this study and analysis of the data. Then, I provide a brief overview of the research design used for this study. Finally, I provide definitions of key terms that will be used throughout this thesis.

Modeling

Modeling in science has been described as a process of constructing, refining, and deploying models of scientific phenomena (Cheng & Lin, 2015; Louca & Zacharia, 2012; Nicolaou & Constantinou, 2014; Oh and Oh, 2011). The development of scientific models allows students to engage in a form of scientific inquiry (Halloun, 2007) and requires collaboration as a scientific community (Cheng & Lin, 2015; Grosslight et al., 1991; Schwarz et al., 2009). Gouvea and Passmore (2017) explain how modeling creates a space for active participation in the science classroom, where students do more than just simply learn the content, they actively construct the representations of the phenomena. In this sense, modeling and models play an important role in knowledge construction and scientific reasoning (Nicolaou & Constantinou, 2014; Oh and Oh, 2011). Models, then, are tools used to represent scientific phenomena, communicate ideas, and engage students in problem solving (Cheng & Lin, 2015; Gouvea & Passmore, 2017). Modeling as an activity can take many forms, but the process of mechanistic modeling is of particular interest in this study.

The activity of modeling can occur in a variety of formats, including mechanistic modeling, and modeling can create a space for epistemic agency and ontological innovations. This study focuses on the creation of mechanistic models. Mechanistic models can be described as models that represent the underlying scientific interactions usually by using entities as the 'actors' of the model (Cheng & Lin, 2015; Louca & Zacharia, 2012). Hammer and van Zee (2006) describe scientific inquiry as being the pursuit of "coherent, mechanistic models" (p. 27) where students try to construct a model with a complete gapless story of the science that the model depicts. Russ et al. (2008) outlines a process for developing mechanistic models where students must identify entities to populate their model and define the activities and properties of these entities. The process of modeling often creates a space for epistemic agency (Miller et al., 2018), where students get to collaborate and construct knowledge as a community. Mechanistic modeling and the creation of entities that populate the model also provides an opportunity for ontological innovation (diSessa & Cobb, 2004) where students are able to develop new innovations and ideas to create new categories of objects.

In this study, there is a particular interest not just in mechanistic model building, but in novel mechanistic model building where students employ epistemic agency and create models using ontological innovation. Novel mechanistic models being those created by students from 'scratch', where often they do not look like the scientifically accepted version of the model. The development of novel models often requires inventing entities to populate the model, and therefore requires defining and refining the properties and activities of these invented entities. These invented entities and the process of novel modeling is a unique space for ontological innovation and epistemic agency, which is explained further in the next chapter. In the literature review, I explain the role of mechanistic modeling, ontological innovation, and epistemic agency, and briefly discuss the role of tinkering with modeling.

Tinkering

Tinkering is an activity that is usually associated with engineering and other design tasks (Resnick & Rosenbaum, 2013). In general, tinkering can be thought of as an ad-hoc process of trial-and-error (Quan & Gupta, 2020) that, I will argue, could be carried out in any design process. In this study, I will look at the affordances that tinkering brings to the science classroom, particularly within model building activities. Tinkering is a process that allows students to try out ideas, experiment, and author their own goals (Petrich et al., 2013; Resnick & Rosenbaum, 2013; Vossoughi et al., 2013). Providing a "low barrier" environment (Vossoughi & Bevan, 2014, p. 4) for experimentation like this is often essential for allowing students to develop novel models. Tinkering is also described as being inherently playful (Beckwith et al., 2006; Quan & Gupta, 2020; Resnick & Rosenbaum, 2013) and this creates a "potentially deeper sense of challenge, purpose and possibility" (Vossoughi et al., 2013) for students to explore and discover in. The activity of tinkering creates a space for iteration where all ideas are taken seriously and 'mistakes' are framed as drafts, thus creating a space rich in insight and new innovations (Vossoughi et al., 2013). Finally, tinkering is often a goal driven process

(Petrich et al., 2013; Quan & Gupta, 2020; Vossoughi et al., 2013) where students learn to persist in problem solving in order to design solutions towards a desired goal. With these ideas in mind, I construct my own definition of tinkering to use for this study that captures the main themes seen throughout the literature.

In this study, tinkering will be defined as an iterative process with a playful orientation, where students improvise with ideas and analogy to pursue emergent or shifting goals. While tinkering is typically thought of as an activity that requires physical objects, I propose that students can tinker with ideas. Furthermore, I suggest that the process of "idea tinkering" could be a vital component to constructing novel models of scientific phenomena. Tinkering has also been described as a "socially rich activity" (Espinoza, 2011; Vossoughi & Bevan, 2014; Vossoughi et al., 2013), and therefore can engage students in collaborative design in the science classroom. In the next section, I will provide a more thorough review of the literature around tinkering and discuss the role that tinkering will play in this study.

Purpose

The purpose of this study is to propose a kind of activity, called "idea tinkering," to describe a productive form of interactions with ideas and peers that students use when constructing models. In doing so, I explore the intersection between model building and tinkering, with explicit attention to how model building benefits from tinkering with ideas. Tinkering is an activity and construct that comes from the world of engineering and is often undertaken with physical objects. The purpose of this study is to collect evidence to determine if it is possible to tinker with novel theories of scientific models and theoretical objects (ideas). Furthermore, I will examine the implications of tinkering on model building and as a practice in the science classroom. How tinkering impacts the development of coherent mechanistic models is a present gap in the literature for both modeling and tinkering. Tinkering in the science classroom is also something that has been overlooked and warrants more attention. This study aims to explore these gaps and provide insights for the science classroom and beyond.

This study is particularly relevant to teachers as they implement Next Generation Science Standards (NGSS)-aligned instruction (NGSS Lead States, 2013). While there is a clear emphasis on modeling in NGSS, most approaches to modeling do not involve the kind of creative, playful, iterative processes that tinkering allows, that I identify in this thesis. Pedagogical approaches to modeling often have students creating representations of scientifically accepted models using scientific terminology and predetermined entities. In the novel mechanistic modeling approach employed by this study, students get to invent terms and entities to their models in the pursuit of understanding the underlying mechanism of a scientific phenomenon through the process of tinkering with their model and their model's entities. The exploration of tinkering with mechanistic models can provide insight on how to better engage students in engineering practices (like tinkering) and provide a creative avenue for student agency in modeling to align with NGSS standards.

Research Questions

For this thesis, the main research question was born out of the need to encompass the two main themes that emerged from the data, these themes being the construction of scientific models and the emergent activity of tinkering with theoretical objects (ideas). The main research question is as follows: **When students are developing models of**

scientific phenomena, is there evidence that their activity has parallels to 'tinkering' from engineering contexts?

I use this research question as a lens through which to view my data, results, and construct my research design. From this main research question, several sub-questions emerged in the hope that these questions would provide more clarity to both the data and the results. All of these research questions come to influence my methodology and the theoretical framework through which the data is viewed. My goal in this thesis is to address these research questions and provide insights to the answers that they reveal.

Sub-Questions

a. How is tinkering with models similar/different from tinkering with physical artifacts?
b. What is the importance of these theoretical objects for tinkering and possibly modeling?

Research Design

This study is part of a larger study that looks at the role of engineering during inquiry in an undergraduate science classroom. This study, in particular, will explore a practice commonly seen in engineering: tinkering. When exploring topics of light and color students aim to develop a coherent mechanistic model. In pursuit of this model, I propose that tinkering emerges and aids students in the construction of their model. I explore these ideas further using a multiple case study qualitative design approach and sociocultural theoretical framework, which are outlined in the paragraphs below.

Model building is an activity that requires collaboration and collective understanding of the same ideas. With this in mind, analysis of the data in this study is viewed through a sociocultural lens. During model development, students persist in problem solving and this often requires social interactions and productive class conversations. Building a classroom culture is also an essential component of getting students to share ideas and experiment with novel versions of their models. Using a sociocultural perspective provides a way to see how social interactions and culture among students influence model building, and what aspects lend themselves towards tinkering with ideas.

Data for this study was collected from two separate semesters of the same university pre-service science teacher methods course. Each semester constitutes an individual case; therefore, this study employs a multiple case study research design. Cases were selected based on richness of the data including student notebooks and class conversations. Data collected for this study consisted of all qualitative data including photographing student notebooks, videotaping or audio recording of all class sessions, and transcription of class conversations. One transcript of a class session was chosen for each case and was analyzed using two rounds of coding. Sessions were chosen due to rich conversation among students and productive advancement in model building. Coding consisted of an emergent round of coding (Elliott, 2018) and a selected round of coding (Saldaña, 2016). Selected codes were used to identify if tinkering was happening in moment-to-moment student interactions, therefore the selected codes were chosen from tinkering literature, and are based on the definition of tinkering used in this study. Results are presented for each case, and data is examined for each of the selected codes. Common themes that emerged from the data are discussed in the discussion section and conclusions are drawn based on these themes.

Definitions of Key Terms

These key terms comprise the foundation of this thesis and provide the basis for which this research is built. In the literature review that follows, I will provide more detailed definitions of tinkering and modeling, as used in the literature. Simplified definitions of tinkering and modeling are included here, along with some other key terminology that will be used throughout this thesis.

- Modeling- A practice of both science and engineering, where students use and construct models as helpful tools for representing ideas and explanations. These tools include diagrams, drawings, physical replicas, mathematical representations, analogies, and computer simulations (NGSS Lead States, 2013). For the purposes of this thesis, I will focus on mechanistic models (Russ et al., 2008) as described further in the literature review below.
- Tinkering- For the purposes of this study, tinkering will be defined as *an iterative process where students have shifting goals, a playful disposition and supply improvisational ideas and analogies*. This is a unique definition constructed from themes commonly seen across the literature on tinkering.
- Theoretical Objects- The invented entities of a model that perform activities acting out the mechanism of that model (Russ et al., 2008). For example, in scientific models of light and color the entities are generally photons (light particles), molecules (dye particles) and cone cells which interact to give an object its color.

CHAPTER TWO: LITERATURE REVIEW

This literature review starts with a theoretical framework to provide the lens through which the data is viewed in this study, and through which the research design was created. In this literature review I will go on to explore what the literature says about modeling in the science classroom, and examine how students are typically taught to create and use models in science. I will explore the idea that when students develop their own models, they often can create their own ontology using modeling as a vehicle. Furthermore, I will contrast the traditional approach to modeling (in which students come to learn about accepted scientific models) with an approach that allows students to develop their own mechanistic models.

Using literature from engineering and the Maker movement, I will explain the traditional role of tinkering in these fields and provide rationale for why tinkering could be an activity that is widely applied throughout different design processes. I will also explain how allowing students to develop their own models and the process of refining these models mirrors the process of tinkering seen in engineering, but with theoretical objects instead of physical objects. Finally, I will define tinkering for the purposes of this study and explain the type of environment where tinkering (both with physical and theoretical objects) is most likely to emerge.

Theoretical Framework

Framework in Context

In this thesis, there is a two-component approach to the theoretical framework where the first component looks at the broad aims of this study, and the second component focuses on the specific lens through which the study was constructed. For the first component, the study is viewed through the activity of modeling. One of the key goals for scientists is the construction and application of novel scientific models. Extending to students, classes should seek to engage students in modeling, but more specifically in the development of their own models of scientific phenomena (NGSS Lead States, 2013). The position I take is that the process of model generation is a kind of design activity, similar to design in other fields (engineering, business, art, and teaching design). For the science classroom, the design of novel mechanistic models is authentic to building rich scientific knowledge, and yet is an activity that students rarely get to engage in. In fact, not all design activities are prescriptive or linear, and many times designing scientific models leads to more creative and improvisational "tinkering" type activities. In this thesis, I look for not only these more structured design activities that promote model construction, but also the more playful, emergent, ad-hoc 'tinkering' approach to design as well.

The second component of this theoretical framework is built on sociocultural theory. In terms of the broad theoretical framework this extends to thinking about sociocultural theory in the science classroom. In this regard, activities in the science classroom should be structured in a sociocultural context where ideas are proposed, vetted and developed, similar to how scientists would structure activities. Naturally, this leads to the interest in modeling, the activity of generating a model, and not the static models themselves. Using a sociocultural perspective, I view learning and knowledge generation as something that happens within groups of students and teacher(s) as evidenced in the moment-to-moment interactions of the overall classroom community. Therefore, I focus on video data and class conversation transcripts as essential artifacts to showcase the power of student discourse and interactions in supporting learning. Furthermore, learning communities use a variety of tools for the transmission of culture and knowledge within the classroom, but they also *create* tools for this same purpose. It is these created tools, such as language, models, and norms that are the focus of this thesis, specifically in the context of creative and playful ‘tinkering’ activities. In the next section, I will describe the sociocultural theory lens in greater detail and how this lens pertains to the design of this study.

Sociocultural Theory

Scientific inquiry - in classrooms and in research labs - is inherently social, where students and scientists collaborate, construct and test ideas, and challenge, vet and debate those ideas. Learning in general, does not happen in a vacuum, but is achieved through social interactions and the supportive learning culture (Brown et al., 2010). It is with this idea in mind, and more specifically that humans are social creatures, that is the basis of sociocultural theory. Through social interactions the mind is able to construct knowledge, flesh out ideas, and generate powerful representations (Townsend et al., 2018). Because learning is a social endeavor, learning happens as a community where students collaborate, argue, and collectively generate ideas and models. Learning is an enculturation into a community and is necessarily and unavoidably a richly sociocultural activity. In this thesis, I use sociocultural theory as a powerful lens through which I view social interactions and examine how these interactions lead to construction of scientific models and help students engage in collaborative processes like tinkering. Therefore, I look for evidence in video data and transcripts of learning in students' activities and interactions in the social environment of the classroom as they engage in explaining phenomena they find genuinely perplexing.

Many theories and frameworks could be used to interrogate how students construct novel scientific models, but using sociocultural theory points towards examining the construction of models within the activity of the classroom. Sociocultural theory is a particularly powerful lens as it provides a way to examine how social interactions impact learning, and how the culture of the students and the culture of the classroom environment can contribute to knowledge generation. Developed by Lev Vygotsky (1979), sociocultural theory describes how people learn through social processes and the culture that shapes these social interactions. Through sociocultural theory, the development of knowledge is considered an activity that is highly dependent on the individual and the social setting (Scott & Palinscar, 2013). Through interactions as part of a community, learners are able to grapple with difficult ideas, extend each other's thinking, and collectively work towards solutions for complex problems. It is through the community and the social endeavor that students' limits expand, and the collective group is able to engage in meaning making together, creating innovative and revolutionary ideas. Science is a field that inherently embodies this idea of social interaction; therefore, it is natural to use a sociocultural lens to study the ways in which students come to explain scientific phenomena.

Within sociocultural theory, researchers focus on both social interactions between individuals and the broader culture in which those are situated. One important aspect of social learning is that it allows students to co-construct tools to use during sensemaking called semiotics which include language, drawings, models, and symbols just to name a few (Wertsch, 1991). The semiotic tools then contribute to the overall culture of the social group and aid the group in pursuit of difficult tasks. While the group, as a unit, establishes a type of culture, the individual students also bring their own personal culture to group dynamics. Students do not walk into any classroom as blank slates, instead they enter bringing with them a wide range of experiences, ideas, and identities. In fact, students add to the culture of social interactions through their own personal funds of knowledge. *Funds of knowledge* are the life experiences, family customs, and identities that students bring into the classroom (González et al., 2006; Hogg, 2011; Moll et al., 1992). Students' funds of knowledge include rich resources about the scientific world and ways of modeling and understanding that world. When considering the culture in a sociocultural context, it is important to consider the marriage that exists between a student's personal culture (funds of knowledge) and the created culture of the class community. It is in a complex culture that social interactions unfold and new ideas manifest, allowing students to create novel designs and engage in real-world problem solving. The interdependence of social and cultural is what ties sociocultural theory together and provides an exciting context for which dynamic learning environments can be viewed.

Using a sociocultural perspective allows me to examine modeling and tinkering as socially enacted practices in the science classroom. While both modeling and tinkering can be accomplished individually, they are rooted in social interactions and the unique culture of the small groups and the larger class communities in which they take place. The remainder of this literature review outlines the importance of modeling and tinkering, as well as establishing how both activities will be used in this study.

Modeling

The development and use of models is a practice that is fundamental to scientific activity (Cheng & Lin, 2015; Gouvea & Passmore, 2017; Halloun, 2007; Nicolaou & Constantinou, 2014). Since the introduction of the Next Generation Science Standards (2013), modeling has been considered an essential practice that students must engage in within the science classroom. The introduction of required modeling in the science classroom sparked a wave of research into ways to engage students in modeling, learning progressions for modeling, examining the types of models that students use, and the benefits and deficits of using modeling. In this section on modeling, I aim to explore a small subset of this research to look at what modeling looks like in science with a focus on students' construction of mechanistic models, and the role of ontology in designing novel models. By the end of this section, I will explain the importance of modeling and how modeling, and various aspects of modeling, fit into this study.

Modeling in Science Education

Briefly, a scientific model, as defined by the Next Generation Science Standards (NGSS) (2013) is a practice of engineering and science where students use and construct models as useful tools for representing ideas and explanations. Furthermore, NGSS (2013) goes on to explain, "These tools include diagrams, drawings, physical replicas, mathematical representations, analogies, and computer simulations". Therefore, models can take many forms; for the purposes of this research, I am interested in mechanistic models and mechanistic reasoning (Russ et al., 2008) as a particularly important hallmark of scientific inquiry. Though my focus is on students' development of mechanistic models, and how designing mechanistic models supports tinkering activities, I will briefly zoom out to view what the literature says about modeling in the science classroom.

Across the literature in science education, modeling is thought of in a variety of ways, but most agree that a model is a representation of some kind of scientific phenomenon (Cheng & Lin, 2015; Matthews, 2007; Oh & Oh, 2011; Schwarz et al., 2009). Oh and Oh (2011) simplify this definition even further by saying that a model is, "something that represents something else" (p. 1112). Models are often used in the classroom as tools to represent mechanisms and interactions of a target phenomenon (Cheng & Lin, 2015; Louca & Zacharia, 2012; Oh & Oh, 2011; Schwarz et al., 2009). Modeling is frequently described as a practice essential to science (Gouvea & Passmore, 2017; Halloun, 2007, Russ et al., 2008) where students are able to develop and use models as a way to build scientific knowledge and represent the world around them (Gouvea & Passmore, 2017; Grosslight et al., 1991; Nicolaou & Constantinou, 2014). Cheng and Lin (2015) describe modeling as "an iterative process of construction, evaluation, and revision of models" (p. 2456) where students continuously make tentative versions of their models that they modify to fit empirical evidence. Models, while occasionally thought of as tangible artifacts, can also be mental models which are the internal representations of scientific ideas (Louca & Zacharia, 2012). In turn, modeling is deeply rooted in knowledge building and epistemology (Cheng & Lin, 2015; Oh & Oh, 2011; Schwarz et al., 2009). Nicolaou and Constantinou (2014) explain how modeling helps facilitate students' learning of science, helps build an awareness of the process of scientific reasoning, and aids in acquisition of conceptual knowledge. For this study, I aim to focus on the construction of mechanistic models, which I will outline in greater detail in the next section.

Mechanistic Models and Mechanistic Reasoning

Models and modeling can take on many different forms in the science classroom, but one form that is of particular interest for this study is mechanistic models. Hammer & van Zee (2006) note that scientific inquiry can be described as the “pursuit of coherent, mechanistic models of natural phenomena” (p. 27). In this quote, the use and pursuit of coherency is particularly important as students often struggle to create a complete ‘gapless’ story of the mechanism of a target phenomenon. In unpacking what constitutes a mechanistic model, Louca and Zacharia (2012) characterize them as representations of physical phenomena including the entities and processes that underlie the phenomena. Furthermore, it is the externalization of this representation (the model) that allows students to process and understand the mechanism and construct scientific knowledge (Louca & Zacharia, 2012). In line with designing mechanistic models is the idea of mechanistic reasoning, or how students are thinking about the mechanism of model, usually monitored through student discourse. Mechanistic reasoning is simply a student’s explanation and understanding of how things work (Russ et al., 2008). There is a natural coupling that occurs between design of mechanistic models, and the practice of mechanistic reasoning. For students to be able to explain their model, they must develop an understanding of the mechanism, and be able to articulate how the mechanism works

(Russ et al., 2008). In this study, there is a focus specifically on mechanistic model building, but in students' explanations of their models they engage in mechanistic reasoning. Furthermore, refinement and modification to the mechanistic model is often spurred by students' mechanistic reasoning.

The process of developing a mechanistic model requires several specific steps, which have been outlined by Russ, Scherr, Hammer, and Mikeska (2008) as a coding scheme to identify mechanistic reasoning in student discourse. Though this schema is designed for monitoring student discourse, it outlines the steps necessary for constructing a mechanistic model. The five distinct steps of mechanistic model building include: 1) describing the target phenomena, 2) identifying the setup conditions of the model, 3) identifying the entities of the model, 4) identifying the activities for the entities, and 5) identifying the properties of the entities (Russ et al., 2008). While describing the target phenomenon is important for mechanistic reasoning, for modeling, the phenomenon is often provided to the students, and their task is to identify the most interesting or essential part that they will model. Identifying setup conditions is creating a space where students can run the mechanism of their model, this could be a physical space, a computational space, or even just a space where students can collaborate and work through ideas. Identifying the entities of a model requires students to identify the 'players' in their model, which in most cases is given to students (photons in a model of light, molecules in a physics model of gas, and enzymes in a biology model of a cell). Along with identifying the entities in the model, students must identify the activities that these entities can do, these are the "actions and interactions that occur among entities" (Russ et al., 2008, p. 512). Finally, students must identify the properties of the entities in the model, these are the characteristics that the entities possess. This is not necessarily a linear process as students may use the activity of an entity to further define that entity's properties, or the other way around. While this process is used to construct mechanistic models, it is employed in a slightly different way in this study.

The process of modeling with ideas and various versions of a model often requires attending to two different aspects of mechanistic models: the entities of the model (and their properties), which often (but not always) have to be invented by the student, and the mechanisms by which those entities produce the phenomenon. Students, therefore, must attend to the creation of the objects or "entities" and the determination of the subsequent activities that these objects are permitted to do within the model. This process mimics that of mechanistic reasoning outlined by Russ, Scherr, Hammer, and Mikeska (2008), where students use predetermined entities and activities to flesh out the mechanism of a particular scientific phenomena. However, I anticipate that when students engage in tinkering with their model, the more emergent and improvisational the entities will become, where students suggest novel objects (houses, pacmen, etc.) as the actors in their model. The second aspect students attend to is the pursuit to understand the mechanism that underlies the phenomenon. In this sense, the entities and their activities are required to act out and establish the mechanism. However, often as students are constructing their model and running the mechanism, they identify gaps where they must define an entity's properties further in order for the mechanism to work. Furthermore, the inventing and defining of the entities can lead to better understanding of the mechanism. Therefore, the entities and the mechanism of a model are interdependent and work to 'bootstrap' along the development of the model.

A Challenge of Modeling

Modeling in science is a practice that affords a lot of opportunities for student agency and creativity, where students make novel discoveries and turn these into mechanistic models. As an activity, modeling allows students to explore mechanisms, develop ideas, and construct scientific knowledge (Cheng & Lin, 2015; Halloun, 2007; Nicolaou & Constantinou, 2014; Oh & Oh, 2011). A modeling space can, therefore, be a unique place for student epistemic agency. Miller et al. (2018) describes epistemic agency as being a meaningful contribution to knowledge building, and a student's ability to "shape and evaluate knowledge" (p. 1057). Epistemic agency is a practice of community where students have the authority in a class to generate ideas and sensemake towards knowledge construction. The modeling of scientific phenomena creates the possibility of epistemic agency in the science classroom where students get to engage productively during problem solving, with the goal of building new knowledge about a phenomenon (Miller et al., 2018). Creating a setting for modeling and epistemic agency does not always lead to production of scientifically accepted models, as the creativity inherent in epistemic agency can produce novel results.

In the class described in this study, students are given freedom and epistemic agency to create a mechanistic model of light and color, and often this produces unexpected and unconventional models. The result of novel models is a challenge of modeling, as students come to the science classroom with prior knowledge about well-known models and the phenomena in question (Olympiou, Zacharias & deJong, 2013). However, engaging in mechanistic modeling of abstract phenomena can produce models that do not map or relate to the scientifically accepted model. For example, in one case in this study students create a mechanistic model of light and color that uses little men and houses as entities, and in another case, students have entities of pacmen and bbs. This differs from a typical science model of light and color that would use predetermined entities of photons and molecules. The goal is to encourage and support students in designing these novel models with invented entities. The challenge lies in getting students to divorce themselves from previous modeling experiences in which they were being guided towards a normative scientific model and employ their epistemic agency to generate new knowledge and produce novel models. Having students engage in modeling and use their epistemic agency to produce models is a unique experience that is authentically scientific, but uncommon in the science classroom.

Importance of Ontology

Mechanistic modeling requires the identification and refinement of entities and their activities, with novel models having to invent these entities. Russ et al. (2008) explains how mechanistic modeling must have entities as the ‘actors’ of the model, and these entities must have defined properties and activities in which they act out the mechanism of the scientific phenomenon. In novel model building, these entities must be invented, and often they are not recognizable categorized objects from a scientifically accepted model, but are abstract theoretical constructs (henceforth called theoretical objects). These theoretical objects are intricate entanglements that are required to populate the model and ‘act’ out the mechanism. Entities in novel mechanistic models are not so much predetermined objects, but are carefully constructed theoretical objects, that manifest and are accepted as students build knowledge and develop their model. This process of inventing theoretical objects is highly creative and collaborative, where one student poses an idea, and the class community grapples with how the idea will fit within the model. In pursuing “coherent, mechanistic models” (Hammer & van Zee, 2006, p. 27) and constructing theoretical objects, students engage in a cognitively rich sensemaking activity that is deeply scientific.

DiSessa and Cobb (2004) originated the term “ontological innovation” to explain how science finds and creates categories of ideas or theories. During mechanistic model construction in this study, students tend to do a similar kind of activity by developing the theoretical objects that inhabit their model. Below is a summary of diSessa and Cobb’s (2004) idea of “ontological innovation”, I will then explain how this idea fits into the process of mechanistic modeling.

They describe the idea as follows:

> The idea behind ontological innovation is deceptively simple. Science needs its own set of terms or categories to pursue its work… "force," "gene, "natural selection," "molecule" "element," "catalyst." The process of creating such categories, however, is far more complicated than writing down a definition, or finding a relevant meaning in a dictionary. Instead, defining the technical terms of science is more like finding and validating a new category of existence in the world; hence we use the term ontological.
>
> The essential challenge can be expressed simply enough. Scientific terms must "cut nature at its joints." That is, they must make distinctions that really make a difference, ignore the ones that prove to be inconsequential, and enable us to deepen our explanations of the phenomena of interest. We must develop theoretical constructs that empower us to see order, pattern, and regularity in the complex settings in which we conduct … experiments. Ontological innovations are attributions we make to the world that necessarily participate in our deepest explanatory frameworks (p. 84).

Developing a model using ontological innovation, then, is not just noting the interactions between constructs, it is creating the constructs and engaging in the iterative process of refining them. Ontological innovation, then, is how scientists carve up the world into sensemaking packets and categories of ideas to develop theories and build scientific knowledge. So, a student's model, the theoretical objects in that model, and the activities that these objects can perform are interrelated and work in tandem to advance the development of the model. One of the goals of this study is to identify the role that theoretical objects and their construction might play in tinkering and mechanistic modeling. In the next section, I discuss how the literature views the activity of tinkering and explain and define how tinkering will be used in this study.

Tinkering

Engineering Design

In engineering education, students are taught *how* to design, instead of assuming that students understand the procedure to accomplish the complex design process (Chin et al., 2019; Li et al., 2019). This is often not the case in science, students are expected to know how to design an experiment without explicitly being taught (Li et al., 2019). Design has recently gained traction in education particularly within STEM education (Chin et al., 2019; Goldman & Kabayadondo, 2016) as a process that has universal aspects and should be taught to all students across the curriculum (Razzouk & Shute, 2012). This is not to say that design in every field will look the same, as scientists often design experiments, models, representations, and theories, while engineers design tangible objects, prototypes of those, and broader structures and systems. What links the two – design in science and design in engineering – is that both engineering design and scientific design involve complex problems with no one "best" solution, and that, in both cases, design is something that can be taught. Since design is a process that teaches valuable skills, it is an activity that should be taken more seriously within the field of science, where students are explicitly taught how to design well-developed experiments and scientific models (Brown, 2008). In this thesis, I examine how students design models and the affordances that the design process produces in terms of engaging in scientific inquiry and knowledge construction. Design becomes an integral part of generating mechanistic models and allowing students to engage in a form of novel tinkering.

One area of design that is particularly important in science is the design of scientific models which represent complex processes and provide clarity to abstract scientific concepts (Stroupe, 2014). Within the science classroom, students rarely have authentic opportunities to design novel mechanistic models; when they are engaged in designing models, it is often highly structured so that students reproduce existing scientific models, and students lack the epistemic agency inherent in design (Miller et al., 2018). Much of this epistemic agency can be gained by testing ideas and creating prototypes, which is essential to the design process in both engineering and science (Elgin, 2013). Part of generating and testing out ideas often emerges through the act of tinkering. In fact, tinkering with ideas (in scientific modeling) and materials (in engineering) is a creative playful process where new designs (especially models) materialize and mature. The problems and phenomena that scientists are designing for are not one-size-fits-all, there is no 'right' solution, the ideas are inherently messy and difficult; this is where tinkering comes in. Tinkering provides an avenue for messy solutions, experimentation and ultimately refinement of designed models (Petrich et al., 2013). Tinkering can be defined in a variety of ways from a mindset, to an activity, a process, or even a disposition. In the next section, I will describe how tinkering is defined in the literature and how tinkering will be defined for the purposes of this study.

Defining Tinkering

While much of the work in design education in engineering has focused on the step-by-step processes that engineers use, there is a growing awareness that these formal activities do not fully capture all aspects of the design process. In engineering and, more recently, the Maker movement (Anderson, 2012; Blikstein & Krannich, 2013), tinkering – the exploration of ideas, materials, and solutions in a playful and iterative process – has come to be seen as a critical activity (Bevan et al., 2015; Petrich et al., 2013; Resnick & Rosenbaum, 2013). Tinkering provides students the opportunity to develop designs and ideas by working through emergent problems and generating novel solutions. Tinkering is a continuous process, one where students persist in difficult goal-oriented design spaces to produce artifacts from iteration and experimentation (Bevan et al., 2015; Quan & Gupta, 2020: Resnick & Rosenbaum, 2013). Unlike the prescriptive process of engineering design, tinkering is more improvisational and ad-hoc where students try out ideas, are creative, and collaborate around a centralized goal (Vossoughi & Bevan, 2014). Unlike engineered designs that follow a prescribed process, tinkered designs tend to be more like bricolage – assembled on the fly with available materials, producing just "good enough" prototypes.

While tinkering might look chaotic or unstructured from the outside, studies show that engaging in tinkering is a cognitively rich activity and encourages the development of new knowledge and understandings about materials and scientific phenomena (Bevan et al., 2014). Petrich, Wilkinson, & Bevan (2013) characterize tinkering as a process of "becoming stuck and then unstuck" (p. 55) where students develop theories and purpose by attempting ideas, struggling, and achieving a breakthrough. Allowing students to engage in the process of tinkering provides authentic opportunities for epistemic agency where students grapple with ideas and evolving constraints that are not often seen in the science classroom, allowing for rich development of persistence in problem-solving.

For the purposes of this thesis, I will operationalize tinkering as a playful, improvisational, iterative process where students have shifting goals based on problems that arise and gaps in their knowledge. Tinkering often lives where design is prevalent, particularly within engineering (Blikstein & Krannich, 2013; Resnick & Rosenbaum, 2013). However, the different components of tinkering are seen in the science classroom, and the process of tinkering could easily lend itself to students engaging in scientific theory building and more novel experimental designs. Tinkering in the science classroom would provide the same affordances that we see within engineering; that is a playful space for trial-and-error where students generate creative solutions for evolving problems. While tinkering is considered an activity that requires the manipulation and design of physical objects (Resnick & Rosenbaum, 2013; Turkle & Papert 1990), it could easily be mapped onto theoretical objects and aid in the development of scientific models. In this thesis, I examine transcripts of class discussions to identify if students are able to 'tinker' with the theoretical objects they have created and determine the role of this 'tinkering' for the development of mechanistic scientific models and theories.

<u>Students as Theorists: Why Tinkering Matters in Construction of Scientific Models</u>

Tinkering is a creative and cognitively engaging activity (Quan & Gupta, 2020), and has potential to be productive for model building and knowledge construction in the science classroom. In this section I outline why tinkering could matter in the science classroom and discuss the various affordances that it may provide. I suggest that tinkering matters in the science classroom because it is one way in which students can build novel mechanistic models. I anticipate that the activity of tinkering with ideas allows students to make mistakes, iterate, and play. Tinkering also has the potential to create a unique space of epistemic agency, where students are encouraged to put forth bold ideas and try out a multitude of possible theories. Finally, tinkering can support student engagement by being a low-stake, rough, just good-enough kind of activity with high rewards in the form of model progression and knowledge construction. In this sense, students are permitted to bootstrap ideas together in the pursuit of a coherent mechanistic model. Below, I outline these ideas further and highlight why tinkering might matter in the science classroom.

Tinkering as an activity 'lowers the stakes' (Vossoughi & Bevan, 2013), in the context of model development, this may provide a space where students can make mistakes, try out theories, and expand their understanding. As an activity, tinkering is built on the process of iteration, where a tinkerer must work through a number of prototypes before reaching the desired outcome (Resnick & Rosenbaum, 2013). Because iteration is an important component of tinkering it allows students to make failed attempts and mistakes and view these attempts as drafts that can be continually modified and improved upon (Vossoughi et al., 2013). When modeling, being able to make drafts of models and ideas would provide a low stakes environment for students to experiment in. I anticipate that the ability to experiment with different theories allows students to modify and improve their models over time while developing scientific knowledge.

The design of a scientific model is a complex process of the development of scientific ideas. Often in model construction, students tentatively adopt novel ideas or entities as the objects of their models in a trial-and-error procedure in order to advance the construction of their models. Students frequently joke, hedge, and suggest analogies that further the construction and the mechanism of their models. This ad-hoc process is characteristically playful and allows students to sensemake as a community. Many of the discursive moves support epistemic distancing from more rigid academic models (Conlin & Scherr, 2018). Further development of complex mechanistic models often requires students to embrace a particular theory of their model, treating it as true and exploring the consequences (a process described by Hammer and van Zee (2006) as "foothold ideas" (p. 26-27)). By proposing, using, refining and modifying these ideas, students gradually assemble a mechanistic model of the phenomenon. Using foothold theories allows students to make progress on model development and knowledge construction.

Tinkering when designing a model would then be inherently creative and affords a level of epistemic agency not seen in many other classroom scientific activities (Russ et al., 2008). With this epistemic agency, students are permitted to explore ideas in a unique way from the freedom fundamental to tinkering. This suggests that tinkering provides a platform where students get to design from the ground up, vet ideas, and iterate from emergent problems. As a part of epistemic agency, students get to develop the characters (theoretical objects) of their models and retrofit these characters to the different environments that their model encounters. I suggest that providing students with this kind of epistemic agency and choice allows them to explore the more creative practices of science and engage in cognitively rich theory building. In the next section, I delve further into the type of environment that might support tinkering and novel model building.

Environment for Tinkering

In studies of tinkering in engineering contexts and Maker spaces, Resnick and Rosenbaum (2013) outline three elements that tinkering activities exhibit: immediate feedback, fluid experimentation and open exploration. While these elements were outlined based on tinkering with tangible artifacts or prototypes, these elements could easily be applied to tinkering with theoretical objects and model building. In fact, the intentional support of these elements could lend themselves to producing a learning environment where tinkering is expected and flourishes. Because Resnick and Rosenbaum (2013) provide an open and interpretative process of tinkering, using these elements of immediate feedback, fluid experimentation, and open exploration could be a recipe for creating a class environment that is conducive to tinkering with both tangible and theoretical objects.

From the examination of two case studies of students' models, it is expected that, when given the opportunity, students are capable of designing creative and accurate scientific models of complex abstract ideas through the use of tinkering. I notice that through the process of designing a model and tinkering with ideas, students are able to develop novel scientific ideas where there is no 'right' answer but a series of possible correct answers, which serve to improve their understanding of a phenomena and increase the depth and accuracy of their model. In this thesis, I will examine data through the lens of immediate feedback, fluid experimentation, and open exploration to identify how these elements translate to tinkering with theoretical objects.

Summary

Science as a practice is messy, unrefined, and collaborative allowing for organic social interactions and innovative construction of scientific ideas. When students engage in scientific inquiry they often work together in social interactions and develop a unique culture that speaks to the individual students and the history of science. This makes sociocultural theory an essential lens to view the interactions within the science classroom and come to understand how the social and cultural piece entwine to promote learning and intrigue. In this thesis, I examine how students construct scientific models while engaging in tinkering with theoretical objects. The act of model generation is inherently collaborative requiring extensive refinement and revision as a scientific community. While engaging in acts of tinkering students must develop the theoretical objects of their model and this requires consensus from the class, where eventually students develop whole classes of objects (ontological innovation) that allows them to apply their model to a wide range of scientific phenomena. Based on the social aspect of much of the data that is collected in this study, sociocultural theory is a lens that allows closer examination of social interactions and provides a framework in which data can be analyzed. Using sociocultural theory, I will look at how students interact to produce models and engage in tinkering, and how these interactions further the development of scientific knowledge.

CHAPTER THREE: METHODOLOGY

Overview

This study takes place as part of a larger study that looks at engineering design during scientific inquiry. This study, in particular, focuses on characterizing and examining tinkering as it emerges when students develop mechanistic models of complex scientific phenomena. In this chapter, I will describe the setting of where the study took place, the role of the college course in which the data was collected, and how this course is different from other methods or science courses. Then, I will describe how participants are recruited for the research study, and outline the demographics of these participants, comparing these demographics to the larger trends seen in the STEM field. Next, I will explain the overall research design, describe how data was collected, and elaborate on the data analysis and coding process. Finally, I will end by describing my own reflexivity as a researcher and outline the limitations and assumptions that emerged from this study.

Using a sociocultural perspective as my theoretical framework I will examine how the social interactions, inherent in the process of modeling building and tinkering, contribute to students' ideas and construction of scientific knowledge. Video data and transcripts from student conversations are among some of the most essential data artifacts as they establish the importance of the sociocultural perspective and highlight how learning is a social endeavor. Because data for this study comes from two semesters of the same university course, I use a multiple case study approach to present and analyze the data. Each case is strictly bound by both time, circumstance, and when particular instances of rich student engagement are showcased. Data is also analyzed using a coding framework based on common themes seen throughout the literature on tinkering. Using the codebook created, I am able to look for evidence of tinkering in student notebooks and transcripts of class conversations. Finally, I use my research question and sub-questions as a guide to navigating the data and creating the study design.

Research Questions

The main research question for this study is as follows: *When students are developing models of scientific phenomena, is there evidence that their activity has parallels to 'tinkering' from engineering contexts?* This study is guided in the pursuit of gaining greater insight into the phenomenon of tinkering, and how tinkering impacts construction of scientific models. The following sub-questions were born out of inquiry from the main research questions and aid in guiding data collection and analysis. All of the research questions listed here assist in creating the research design and methodology of this study.

a. How is tinkering with models similar/different from tinkering with physical artifacts?
b. What is the importance of these theoretical objects for tinkering and modeling?

Setting

This study takes place on the campus of Boise State University (BSU) located in Boise, Idaho in the northwestern United States. The campus of BSU is located in the heart of downtown Boise and is surrounded by parks and scenic wildlife with the Boise River running parallel to campus. The course, STEM-ED 350: Research Methods, that is used to recruit participants is part of a required course for a pre-service secondary science teacher preparation program known as IDoTeach, part of the UTeach teacher training network (UTeach Institute, 2022). Students in the Research Methods course come from a wide range of STEM disciplines including chemistry, physics, engineering, computer science, geoscience, and most prominently biology. The course allows students to experience scientific research and collect a unique perspective on pedagogical approaches to teaching science research.

The topic of the course varies, but topics are selected to engage students in a high level of inquiry and are chosen because they are not covered in traditional science curriculum. Some topics of the course include modeling how we measure time, determining the flow of energy in a system, and exploring light and color. The classes used in this research come from semesters that looked at light and color, beginning with the question if "is every color in the rainbow?" and generating models of color that account for this and related emergent questions. The classroom that the course takes place in sits adjacent to a large supply closet, where students have full access to a wide range of materials used for the teacher education program. The materials in the supply closet are often a vital part of students' exploration of ideas and development of their models. The setting of this study plays a critical role in the recruitment of participants, and in participants' agency to develop novel scientific models and ideas.

The Course

The course that is used as the subject of this research is not a typical research methods course, education course, or science course. The course, STEM-ED 350: Research Methods (further known as Research Methods), is a required class for the pre-service secondary science teachers of the IDoTeach program. Upon completion of the

IDoTeach program, students will earn a bachelor's degree in a STEM field of their choice (i.e., biology, engineering, math), and earn a teaching certificate in the same STEM field as their degree. The Research Methods course is a semester (16-week) long class that meets twice a week for 75 minutes at a time, for a total of 150 minutes a week. What makes the course unique is that it has no required text, curriculum, or science lab manual, and is far less scaffolded than typical science courses. The goal of the course is to have students gain experience in building scientific theory and developing novel scientific models of interesting phenomena. Students begin the class by engaging in scientific inquiry through the examination of a puzzling question (e.g., Is every color in the rainbow?) and the support of a curated set of materials (Maglites, colored gel filters, printer inks, etc.). Over several weeks, conversations and investigations that couple the question and the materials lead students to develop a model that can explain what is happening with light and color.

The seemingly laissez-faire open format of the course puts students in a unique situation that they have rarely, if ever, encountered in other courses where students get to productively grapple with the unknown in the pursuit of developing scientific theory and ideas. Students often work in self-assembled small groups or pairs to explore ideas, develop mechanistic models, and conduct experiments. The course meanders in topic due to the materials that students are given and how the materials influence the questions and models that students investigate. In fact, students occasionally explore questions and topics that lead to dead ends, but these dead ends are extremely productive and impact students' models and theory of light and color. Allowing students to muddle through the unknown, go down dead ends and develop foothold ideas (Hammer & van Zee, 2006) that lead to coherent mechanistic models of phenomena is, in some ways, more authentic to the scientific process that 'real' scientists engage in than what these students typically experience in their science classes. The goal of the Research Methods course is to allow students to experience an environment and practices similar to those that scientists engaging in research would experience in order for them to develop their own scientific models and theories.

Participants

Recruitment of participants for this study occurred through the use of the STEM-ED 350: Research Methods course at Boise State University. This course is part of the pre-service STEM teacher preparation program known as IDoTeach that all science majors are required to take to fulfill degree requirements and earn their teaching certification. Students who take Research Methods come from a variety of disciplines including chemistry, physics, engineering, computer science, geoscience, and the most abundant, biology. The chosen disciplines of the students play a role in their knowledge of science and how they approach modeling challenges that they experience in this class. Students are required to take STEM-ED 350: Research Methods to complete the IDoTeach Program, but they are not required to participate in this research study as a result. The instructor of Research Methods explains to students the premise of this study and obtains student's informed consent to participate. Students have the option to opt-out of research at any time, and grades in the class are not based on student participation in research.

The specific participants for this thesis come from two different semesters of the Research Methods class. Both semesters of the class contained very few students, five students and six students respectively. One student in the second semester class chose not to participate in research so the total participants equal ten students. All students in the classes are upper-division students, most having completed multiple years of science labs as undergraduate students, and many having participated in research experiences in practicing science labs. The demographics of the participants were examined to identify the gender, race, and science background of the participant group as a whole, and the individual semesters for better comparison and insight. Across the two semesters of participants, 60% of participants were female and 40% were male, with both semesters having a 3 female to 2 male ratio. These numbers differ from what we normally see in the field of STEM where women are traditionally underrepresented due to a myriad of factors (Kricorian et al., 2020; Rainey et al., 2018; Wang & Degol, 2017). Some of this disproportion in gender could be due to the student's scientific backgrounds as most participants were majoring in biology or life science and these science fields tend to have higher amounts of women compared to other STEM fields (Bloodhart et al., 2020). In fact, 70% of participants were majoring in Biology, 10% in Geoscience, 10% in Chemistry, and 10% in Physics. Across the two different semesters, the first semester was 80% Biology and 20% Physics, while the other semester was 60% Biology, 20% Geoscience, and 20% Chemistry. The participant group lacked racial diversity with 90% of the students identifying as white/Caucasian, and 10% being African American/Black. These demographics are typical of the STEM field with minoritized races and ethnicities (Black/African American, Latinx, Asian, Native American, and Pacific Islander) being traditionally underrepresented (Ma & Liu, 2017; Rainey et al., 2018). Reproducing this study with a participant group that is more racially and ethnically diverse could produce different results due to more diverse student background and wider-ranging funds of identity and knowledge. Participants for this study were not randomly selected as they were recruited as part of a required course for their degree.

Research Design

This study is part of a larger investigation with the goal of identifying where design challenges emerge during scientific inquiry, and how to productively support and engage students in addressing these design challenges. Therefore, our data focuses on the moment-to- moment conversations, interactions, and inscriptions using video and audio recording of the class, and images of students work to track the development of design over time. Initially, the study was focused on design with physical materials (i.e., experimental design and representational models), however, it became clear that students were not only designing physical artifacts, but they were inventing and designing theoretical artifacts as well to produce novel mechanistic models of scientific phenomena. The production of student models and design of theoretical objects therefore became the focus of this study; in particular, students' iterative designs of theoretical objects had parallels to tinkering with physical objects, and this led me to look for evidence of tinkering during the generation of theoretical objects and novel student models.

Following a qualitative methodological approach, this study uses data that is qualitative in nature, including student notebooks, audio and video transcripts, and images of student physical and theoretical design. As part of the qualitative methodology, this study uses a multiple case study design to examine two different semesters of the same undergraduate college course, STEM-ED 350. Creswell and Poth (2016) define a case study as methodology used to design a study of a particular issue, experience or situation, but others (Crowe et al., 2011; Stake, 2013) view it as a deliberate choice to study a particular phenomenon in a real-life setting. For the purposes of this study, a case will be defined as a pursuit to understand a complex phenomenon, particularly instances of tinkering during scientific model construction. Each case begins with students' initial engagement with a puzzling phenomenon. By tracing student interactions and designs to their final scientific model, I am able to describe and explain the complex phenomenon of tinkering with theoretical objects. Data collected consists of a full set of video, audio, and images of student work, and from these a select few moments are chosen for further analysis based on specific indicators of tinkering.

To select the cases, I sought instances in which students actively construct novel models of scientific phenomena, and for which there was rich data of classroom conversations, student work, and interactions. These cases also included time boundaries of a semester and occurred in the same classroom equipped with ample supplies on the same university campus. The first case of the course occurred during the Spring 2020 semester (from January to May) and consisted of five students. The second case of the course occurred during the Spring 2022 semester and consisted of six students, five of whom participated in this research. For both cases, specific class conversations were analyzed through coding, looking for evidence of tinkering, along with in-depth analysis of student notebooks. Below, I describe the data collection, selection, and analysis process in greater detail. It should also be noted that both courses were impacted by the COVID-19 pandemic, specifically in modality of the course and the need for increased safety precautions limiting student interactions. The Spring 2020 semester shifted online in late March, and analysis ended when students' participation moved online. The Spring

2021 semester was specifically excluded as a potential case because the course was fully remote taking place in an online setting, which limited opportunities for students to fully engage in design or modeling. Using the multiple cases presented here, each case will be examined individually, and comparisons will be drawn between the two cases to show how tinkering with theoretical objects can occur during scientific model development.

Examination of the data (transcripts, student notebooks, and physical artifacts) revealed interesting codes and themes from comparison of the two cases and dissection of the cases individually. The first case revealed the playful nature of tinkering with ideas, the importance of analogy in the development of theoretical objects and showed that students can construct novel mechanistic models. The second case revealed how theoretical objects can evolve over time to become whole categories of objects that allow students to apply their model to a wide range of phenomena. The selected tinkering codes were used to analyze the transcripts of class discussions in both cases and revealed that students are able to be iterative, improvisational, playful, and have shifting goals during the development of their mechanistic models. When the two cases were compared, interesting similarities and differences emerged, specifically how tinkering with theoretical objects may mirror the process of tinkering with tangible objects. All of these ideas are detailed further in the results section in the next chapter.

Data Collection

All class sessions were videotaped or audio taped for both semesters of this study. Field notes were also taken during the video or audio recordings to accompany the recordings and provide additional insights and context to the recordings. Field notes were taken by two different graduate student researchers, one being a graduate assistant for the primary investigator of this research during the first semester of the study (Case 1), and the second being the author during the second semester (Case 2). Images and artifacts produced by students, including student notebooks, in-class experiments, and student homework were photographed and archived. Student notebooks were collected at several points during each semester and became crucial artifacts for tracking students' ideas and identifying representations of their models. Student notebooks also played an important role for tracking the development and refinement of student theoretical objects. Images and quotes from student notebooks were isolated and analyzed as essential data and artifacts to explain the process of tinkering.

For this study, a singular class session from each semester was chosen and the video or audio recording was transcribed by Rev.com. Rev uses a computer program to transcribe the majority of the transcript and then a human transcriber checks the transcript to ensure accuracy. The transcripts were checked for accuracy and were reviewed by the author during analysis of the data and any necessary corrections were made to ensure greater triangulation of the data. Several class sessions from each semester were isolated based on the richness of the class discussion and the topics of discussion. One class session from each semester was selected to be transcribed based on student conversations of theory building, model design, and puzzling questions. These class sessions were also selected as they exhibited prolonged periods of theoretical ‘tinkering’ with the students inventing and refining theoretical objects and models. Once the transcripts were received, the data analysis process of coding the transcripts and identifying important themes began.

Data Analysis

The majority of the data used for this study came from two sources, 1) student notebooks showing the respective semester's model of light and color and 2) the transcripts of the selected class sessions where students used invented theoretical objects to design their models of light and color. The student notebooks were photographed and analyzed by multiple researchers to ensure that similar conclusions were reached. The models within the students' notebooks laid the groundwork to allow the rest of the class to be able to design and invent theoretical objects and construct mechanistic models. Several different models across both semesters were identified within the student notebooks and were isolated to show a timeline of how the models evolved. Without the students' model of light and color and the vivid images that the students created, the class would not have been able to make progress on the 'itchy' questions that were raised, and better understand the phenomena of light and color would not have been reached. The notebooks were used as a source of reference and imagery and will be used in the results section as data to explain the students' model of light and color, and describe how students can invent and tinker with theoretical objects and models.

For the transcripts, these particular class sessions were selected to be transcribed based on the rich discussion by students during the class, and steps taken by the students to modify their model during the discussion. In addition, these class sessions stood out for their engagement with novel, theoretical objects and how students used these objects to construct their models. After selection, the transcripts were analyzed through two rounds of coding. The first round of coding used open codes (emergent codes) derived from the text (Elliott, 2018; Saldaña, 2016). This round of coding did not yield any particularly significant results. The second round used selected codes from the literature on tinkering to determine if the students were 'tinkering' with their theoretical objects over the course of the transcripts (Saldaña, 2016). The codes for tinkering are selected phrases (such as iterative or playful) that are commonly seen in definitions of tinkering in the literature. To identify if students were 'tinkering', these identified aspects from the literature (iterative, playful, improvisational, etc.) were used to show that students were doing the work to improve their models over the course of the transcript. Conclusions were mainly drawn from the second round of coding and are described in more detail in the results chapter. The transcripts and coding were important for identifying key moments in model development and student design.

Codebook

Coding was completed using two transcripts of whole class discussion that were selected because they are particularly rich in model development and clarification of ideas. One transcript from each course (case) was selected, and section criteria were based on student interactions (questions, ideas suggestions, and student cross talk). The class discussion in both transcripts occurred in classes that took place late in the semester when the students were focusing on the refinement of their model.

The codes found in this codebook are based on common themes that emerged from the literature on tinkering. Coding of the class transcripts occurred in two different cycles. The first cycle of coding was open coding or emergent coding (Holton, 2007; Moghaddam, 2006) to see if any trends or patterns in the data would appear. From this cycle, I noticed that the use of language (particularly around constructing ontology for their theoretical objects) was important for the development of clear ideas and the design of the students' model. After this initial cycle, coding occurred again, this time using selected codes (Blair, 2015) looking specifically for the elements of tinkering identified from the literature (iterative, playful, improvisational, and shifting in goals).

Table 1 Simplified Coding Framework of Selected Tinkering Codes from Literature

Codebook	
Selected Codes	**Definition**
Iterative	A recurrent theme or idea that is brought up multiple times over the course of a discussion, or over the class as a whole. Usually, the refinement of an idea or change of theoretical object to improve the students' model.
Playful	Comments or ideas suggested by students that allows for the joyful testing of ideas and creates a lighthearted atmosphere. A particular style of engaging in the world where students experiment with ideas in the process of creating something new.
Shifting Goals	An abrupt change in the topic or idea of the conversation, with the clear establishment of a new goal, question, or topic.
Improvisational	The use of spontaneous analogy to fit or describe an idea, avoids scientific terminology. Using common everyday language in creative ways to explain or clarify an idea. Or using prior knowledge and experience and applying it to phenomena in the model.

Reflexivity

The author has worked as both an undergraduate and graduate research assistant during data collection in the STEM-ED 350: Research Methods class that is part of the IDoTeach program in the College of Education at Boise State University. Due to the timing of data collection, the author had personal relationships with many of the students in the Research Methods class but did not interact with any of them during the time of data collection. The author was also an undergraduate student in the same Research

Methods class prior to beginning this research, one year prior to data collection. From these varying experiences, the author has experience being both a student and a researcher in the Research Methods course. When conducting research, the author took all precautions to remain objective (did not have any personal interactions with student participants) and triangulated data with other researchers before drawing conclusions. Conclusions drawn by the author come from multiple sources of data including student artifacts, videos, transcripts, audio recordings and field notes helping to improve triangulation of evidence and reliability of conclusions.

Limitations and Assumptions

One limitation of this research is the data used in this study comes from multiple small classes. One case of a class with five people, and another case of a class with six people. Although there is a multitude of evidence and data to support claims made in this thesis, it is hard to say that results are generalizable as the data was obtained from a small sample size (n), and therefore data cannot be extrapolated to a larger class size or more general population. Another limitation of this research is the ability for the findings to translate to a more 'traditional' science classroom. Engaging students in the development of novel scientific models can be time consuming as there is no prescribed curriculum that outlines this process. The course used to collect data in this study is specifically designed with modeling in mind and engages students in unique practices to develop scientific models. To compensate for the time commitment, the strategies described in this thesis could be implemented in a small-scale unit or weeklong lesson series where the explicit goal is engaging students in ontological innovation and development of their own scientific model for a particular phenomenon.

The final limitation is the participants' knowledge of science, which can hinder their ability to creatively design models and innovate with ideas and theoretical objects. Through this research, I noticed that students with extensive scientific knowledge have difficulty stepping away from scientific terminology and are often reluctant to build new models and representations of well-established scientific ideas. With this in mind, this research is best implemented with students who have little or limited STEM knowledge, or implemented using an abstract science topic unfamiliar to students (e. g. color, energy, time). With more research, specifically into implementation in different classroom settings, a better understanding of tinkering with theoretical objects and design of scientific models can be gained to overcome these limitations and create spaces for scientific inquiry with student agency and ontological innovation.

One assumption of this research is the class that data is collected from, STEM-ED 350: Research Methods, is specifically designed to engage students in scenarios that demand ontological innovation. Topics are chosen to support this, including light, color, timekeeping, and energy in a linear motor. These topics are chosen based on the assumption that students have little knowledge or experience, and therefore they will provide an opportunity for deep exploration and novel development of ideas and models. However, not all scientific modeling, or the development of novel scientific models requires ontological innovation, therefore the Research Methods class is designed and scaffolded to ensure that students have the opportunity to develop their own scientific models and use ontological innovation during this generation process. In fact, it is assumed that students have very specific experiences with modeling in science. That is, I anticipate that students have familiarity reproducing models or developing well-established models in highly scaffolded activities in the science classroom, but scarcely do students get the opportunity to generate unique models of science phenomena. It is rare, as far as science education goes, to create a classroom environment that engages students in these practices authentic to scientific research in such an open-ended way, but it is vital for students to experience these practices and explore the uncertainty that comes from the evolution of scientific ideas and models.

Another assumption from this research is that participants in the Research Methods class have not participated in, or have limited superficial participation in scientific research, therefore the processes (ontological innovation and tinkering with theoretical objects) in this class are new to the students and show a different pedagogical approach to teaching science and engaging students in scientific inquiry discoveries. In fact, even if students have experience in scientific research, they are well-scaffolded experiences where students work in well-established groups with clear protocols collecting mostly quantitative data, in environments that involve little room for innovation or creation by the students. With this in mind, the Research Methods class is set up to provide a new environment where students grapple with the unknown in pursuit of generating and developing new novel scientific ideas and models.

A final assumption is made about our population of students in this study, that these students have the ability to engage with different forms of agency (particularly, epistemic agency) when provided, and that the students culture, ability, experiences and funds of identity come to influences how they view different topics and develop scientific ideas.

CHAPTER FOUR: RESULTS

From data collected using a multiple case study approach, I will show students constructing novel scientific models, and describe how the development of these models, in certain cases, can be viewed as a kind of tinkering activity. Using student notebook data alongside transcripts of classroom discussion, I highlight from these moment-to-moment instances evidence for tinkering. To begin, I will provide the canonical scientific model for the phenomena that students study and point out important features of student models to notice. Then I will explain and provide the codebook that is used as a guide to identify evidence of tinkering. From there, a detailed description of each case and the data from the two cases will be presented, with a specific focus on when tinkering emerged. Using these cases, I will employ cross case analysis to distinguish similarities and differences between the cases. Finally, I will summarize the main findings and consider how the data conveys the overall story of tinkering with theories.

The Science of Light and Color

The students in both case studies spent their semester exploring the topic of light and color, with the goal of developing a coherent mechanistic model that could be applied to a range of scientific phenomena. The unit of instruction on light and color begins by asking students, "Is every color in the rainbow?". Often students can provide a yes/no answer quickly (often answering no because the rainbow does not contain colors such as black, brown, gray, pink, etc.), but students soon realize that they do not have a complete model that can explain which colors are in the rainbow and which ones are not.

This rainbow question is generally a puzzling enough question to sustain interest in the problem over multiple weeks. Students spend a significant amount of the semester engaged in addressing this question, and ultimately the beginnings of their models emerge from the pursuit of an answer.

Briefly, a scientific answer to the rainbow question is that no, not every color is visible in the rainbow. White light, which is split to produce a rainbow, is composed of wavelengths from 380 nanometers (red) to 700 nanometers (violet). Different objects absorb, transmit and reflect different wavelengths of light. And for those that reach the eye, the retina has cones that absorb some of these rays. In particular, there are three different types of cone cells that are sensitive to (that is, absorb and send a signal to the brain) three different ranges of wavelengths; short ("red" wavelengths), medium ("green" wavelengths), and long ("blue/violet" wavelengths).

Many of the colors that we perceive, then, are not 'pure' wavelengths, but are created from multiple different wavelengths of light. The actual color that we perceive is related to both the wavelengths that are reflected from an object and the response from the cells in our retina (cone cells) (Figure 1). For example, magenta objects (the pinkish-purple color used in printer ink) reflect red wavelengths and blue wavelengths from opposite ends of the electromagnetic spectrum. When our eyes (specifically cone cells) perceive this color, it triggers a response from the short cones and long cones, which, when triggered together, the brain interprets as the color magenta (Figure 1). Magenta, therefore, is not in the rainbow, as it is composed of multiple wavelengths, and these wavelengths come from opposite ends of the spectrum. (White, on the other hand, is composed of equal amounts of wavelengths that trigger all three types of cones.) To construct a model, then, students generally have to recognize that:

- white light is heterogeneous, and composed of multiple wavelengths of light
- that these different wavelengths have different ways of interacting with materials (e.g., they can be absorbed, reflected or transmitted, depending on the wavelength)
- that the light that enters the eye is what is perceived
- that the color perceived is related to the wavelengths that are reflected off of an object, together with the cones that those wavelengths activate

Students must work out all of these various mechanisms of light, objects and vision, and find a way to reconcile these into a complete, coherent model of color perception.

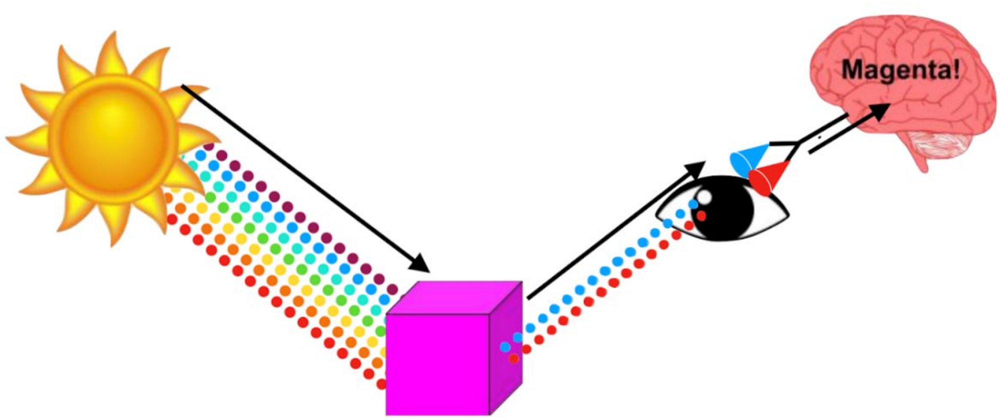

Figure 1 Diagram Showing Color Model
Image showing how sun emits white light containing specific wavelengths (colors), these light particles hit an object (cube) and some are absorbed (the middle of the spectrum, in this case), and some are reflected by the object (blue and red, in this case), then the blue and red light particles are absorbed by different cones in the eye (the long and short cones, in this case). Finally, the cone cells in the eye send information to the brain which interprets this blend as magenta.

When designing a model of light and color, students can be seen addressing a range of ideas that become part of their final model. First, students recognize that they must have a way to represent light; they often develop a vague model that becomes more precise over time. Students begin thinking of light as a stream of particles emitted from the sun or a light bulb, and then create an entity to represent those particles in their model. Other students, usually due to prior knowledge of light and not direct evidence, will describe the light as a collection of 'wavelengths'. However, over time, students in all of the cases described in this thesis use a particulate model of light to describe the phenomena. Then, students typically notice that light particles are interacting in some way with physical objects to cause these objects to exhibit a particular color (green, blue, etc.). Therefore, students must also have a way to represent this property of the colored objects as an entity in their model. The entities of light particles and dye particles become the starting point of student models, and their models develop and change further as they encounter more phenomena. (Note that students generally do not use the words “light particle” or “dye particle” but instead select their own names for these entities and properties.) Generally, later in the semester, students look at how the eye perceives light and color and must adapt their models to account for cone cells as a further mechanism of color perception. In the transcripts below, things to notice about the students’ models include: 1) the particular theoretical objects (entities) that students chose to represent scientific ideas in their models, 2) how these theoretical objects change as the models encounter new phenomena, and 3) how the construction, design, and modification of student models resembles the process of tinkering seen in engineering.

Codebook and Transcripts

Coding was used to analyze transcripts of whole class discussions for both cases. In each case, a specific class session was selected, the transcript was obtained, and the transcript was coded using two rounds of coding. The first round of coding used emergent codes to identify common themes in the transcripts. While the second round used selected codes to look for moments of tinkering. These selected codes were chosen from the tinkering literature, and were identified to be the most necessary ingredients for which tinkering is likely to occur. These selected codes along with the definitions and in vivo examples from the transcripts can be seen in Table 2. From the coding process, I was able to extract pieces of the transcript that best illustrate the selected codes, and therefore the elements of tinkering. These pieces of the transcripts are examined in greater detail in the sections below and in the codebook (Table 2).

In the transcript from Case 1, students discussed two main ideas related to their model, 1) they tried to identify how “little men” (colored light particles) interact with “houses” (dye particles) in a gel filter and, 2) they discussed the idea of ‘user error’ for colors such as magenta where the brain is perceiving one singular color (magenta) when there are actually two colors present (red and blue). It is through the discussion of these ideas that students were able to refine their model and construct new knowledge about light and color.

The transcript from Case 2, focused on the mechanism of how objects glow-in-the-dark. In this transcript, students discussed how “pacmen” (dye particles) in objects must eat special “bb’s” (ultraviolet light particles) and later ‘puke’ them up, with this puking action causing the object to glow-in-the-dark. Throughout the transcript, students tried to work out the mechanism that allows something to glow-in-the-dark. They test ideas, modify their model, and use prior knowledge to identify important features of glow-in-the-dark objects. Students also had to modify the activities (puking) that their theoretical objects (pacman) could do in order for their model to be able to reconcile with reality. By the end of the discussion, students are grappling with unique problems and are able to develop emergent solutions to apply their model to a variety of phenomena.

Table 2 Full Coding Framework Showing Selected Codes, Definitions, and In Vivo Examples.

Codebook		
Selected Codes	**Definition**	**In Vivo Examples**
Iterative	A recurrent theme or idea that is brought up multiple times over the course of a discussion, or over the class as a whole. Usually, the refinement of an idea or change of theoretical object to improve the students' model.	**Case 1:** When trying to define how houses interact with little men in their model, one student states, "There're houses and mirrors or something, trampolines and houses?". Later in the discussion, another student counters by saying, "I think there are obstacles [in houses]". **Case 2:** A recurring idea is puking pacmen, one student explains, "No, for some reason it (a pacman) pukes up green." Another student says, "Puke up some green-ish." And later in the conversation, a student asks, "When would they start puking up stuff?"
Playful	Comments or ideas suggested by students that allows for the joyful testing of ideas and creates a lighthearted atmosphere. A particular style of engaging in the world where students experiment with ideas in the process of creating something new.	**Case 1:** When trying to explain the difference between colors, one student described each color as a "neighbor association", and another student agreed saying, "Green is a college apartment complex, magenta is a 55 + community, and blue is a suburb". **Case 2:** When asked what glow-in-the-dark pacmen eat, one student suggests, "I said that they [pacmen] eat everything, but then they decide to puke up some stuff."

Codebook		
Selected Codes	**Definition**	**In Vivo Examples**
Shifting Goals	An abrupt change in the topic or idea of the conversation, with the clear establishment of a new goal, question, or topic.	**Case 1:** Student interjects another student's explanation, "I have a question. Okay, not a question, more a statement." **Case 2:** One student shifts the conversation away from the mechanism of puking, suggesting, "I was thinking about the bioluminescent organisms in the ocean where there's no sunlight that gets to them because they're so deep down in the water."
Improvisational	The use of analogy to fit or describe an idea, avoids scientific terminology. Using common everyday language in creative ways to explain or clarify an idea. Or using prior knowledge and experience and applying it to phenomena in the model.	**Case 1:** "What if I showed you a Christmas tree with red ornaments and you're like, "That's brown." And I would be like, "It's pretty clearly red and green." **Case 2:** When discussing what color a glow-in-the-dark object is, a student suggests that pacmen, "Puke up some green-ish". Another student improvises with prior knowledge suggesting, "There's other colors for glow-in-the-dark bracelets. You can get pink, you can get orange. I think you can get yellow. There's other neon colors you can get."

Case 1: Little Men and Houses

Case Boundaries

The first case of this study occurred during the Spring 2020 semester. The STEM-ED 350: Research Methods course consisted of five students during this semester. The class met twice a week for 75 minutes each meeting, and the students focused on the topic of light and color. Their ultimate goal was to create a mechanistic model that could explain light and color in a multitude of situations. Class sessions met in-person until March of 2020 (two-thirds of the way into the semester) when the COVID-19 pandemic forced classes to move online. The sudden switch from in-person to online stunted the students' progress on the construction of their model, so explanation of their model will only reflect the model up to this point in the semester. Each class session was videotaped, and student notebooks were photographed for recordkeeping. The transcripts from the videotapes and entries from student notebooks are the two main sources of data in which I will describe model development and instances of tinkering. Sections of transcript and specific student notebook entries were selected because they show element(s) of tinkering or are pivotal in the narrative of model construction.

<u>Timeline</u>

Students began the semester by grappling with the question, "Is every color in the rainbow?". Brown was a particularly vexing color for students in this initial conversation. Using materials provided to the class, including flashlights, printer inks and gel filters (in colors known by the instructor to be particularly generative), along with other materials they could select from the supply closet, students collaboratively worked to understand the abstract scientific concepts that surround light and color. A few weeks into the semester, the students became fascinated by gel filters (Figure 2, left), and wondered how these filters seemed to 'dye' the light different colors. To aid in their exploration of gel filters students used a free software program for image analysis, called ImageJ (Figure 2, right) that produced numerical values for the amount of red, blue, and green light in a digital image (Abràmoff et al., 2004). This software allows students to identify the components of colors present in an image and would later provide empirical evidence that they could compare their model against. One student, Helen, when looking at the image data for a magenta filter was trying to explain the mechanism within the filter that seemed to turn white light to magenta. In doing so, she created a model of light and color where different colored little men (light particles composing white light) were trying to jump over a fence (pass through a filter). In this model, the little men that made it over the fence were the only ones seen and created the color of the filter, leaving the little men that could not get over the fence to be the color that disappeared. For a green filter, all of the green little men would make it over the fence and through the filter, leaving behind the red and blue little men, thus creating the green color we perceive. This was not her first idea of the mechanism of this model, in fact, she tried several possible ways of modeling this, as seen in "options" in Figure 3. After collecting data from ImageJ about a green filter, Helen identifies three ways to interpret this data (Figure 3). Even at this early stage of her model, Helen is developing multiple 'prototypes' to run and test ideas as a way of tinkering with her model. In collaboration with the class, Helen ends up modeling a magenta filter as white light composed of red, green, and blue little men which would hit or encounter the filter, but only green little men would not be able to jump over the fence (go into the filter), letting the blue and red little men through so that the filter appears magenta colored.

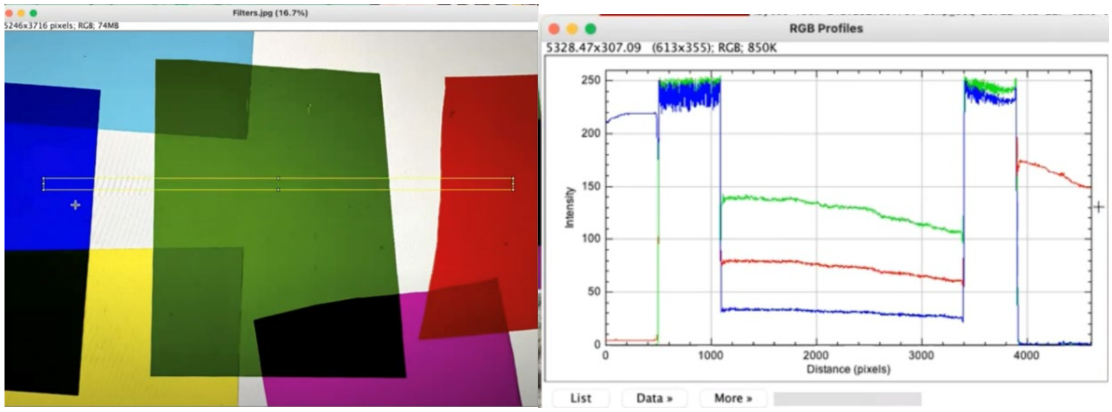

Figure 2 Images Showing Gel Filters (Left) and ImageJ Data (Right)
Left- Photo of different colored gel filters, colors include blue, cyan, yellow, green, magenta, and red, placed on a white computer screen. Right- ImageJ graph showing red, blue, and green values present in the gel filters. Values correspond specifically from the yellow box seen in the gel filter photo (left).

Once Helen presented her model of little men and fences to the class, the other students quickly adopted the model and terminology when discussing light and color. That is, there was uptake by the entire class of the terms ‘little men’ as a representation of colored particles of light that compose white light, and ‘fences’ as the element or property of a filter that blocked certain types of “little men”. This terminology, which would be slightly modified, persisted for the remainder of the semester. Over several weeks, the students collaborated to refine and modify the model, until it eventually evolved into colorful little men (“light particles”) that come in “rainbow colors” and houses (dye particles) that can selectively admit (absorb) some men and other colors of men reflect off or pass by. The creation of little men and houses (Figure 4, top) was important for providing a platform where students could openly and authentically suggest ideas and create workable models where they could test the accuracy of these ideas. Through the design of the model, students encountered rich sensemaking opportunities where they had to grapple with abstract ideas and construct explanations that would allow their model to represent real-world phenomena of light and color (specific transcripts and analysis are provided in the following section). In fact, through the iterative process of design, students were able to create a model that could be mapped onto various scenarios of light and color including the pixels in a computer screen, printer inks, and color perception of the eye (Figure 4, bottom).

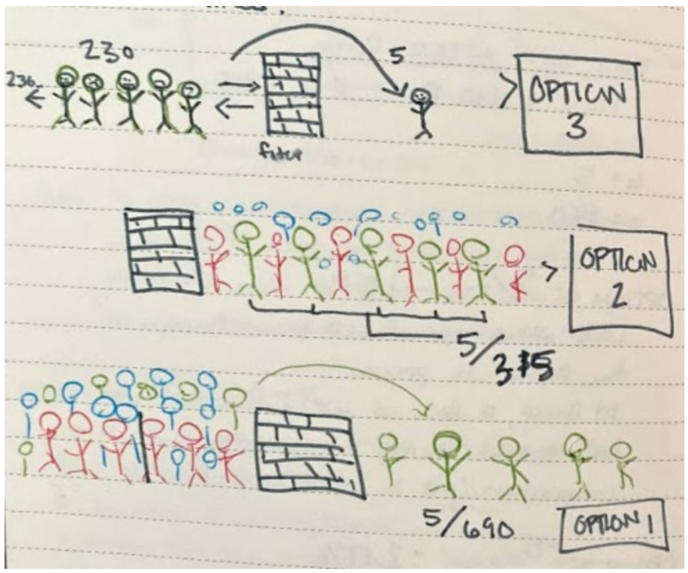

Figure 3 Photo from Student Notebook Showing Little Men and Fences Model Photo from student notebook showing three options of interpreting ImageJ data of a green filter. Option 1 showing that the colored little men that are able to get over the fence end up being the color of the gel filter. For example, green little men get over the fence leaving behind the blue and red little men, and the filter appears green.

The students' model would encounter a range of phenomena over the course of the semester, and students would need to reconcile the differences in their model to the empirical evidence they collected. They first achieved this with the gel filters and the use of numerical data from ImageJ. After gel filters, students began exploring with printer inks (cyan, magenta, and yellow) and tried to determine how these colors in a printer can produce a seemingly complete range of colors when mixed together. Using this same idea, students pondered how the pixels in a computer screen (red, green, and blue) could achieve the same effect of producing 'all' colors on the screen. Finally, students investigated how the eye perceives color by using cone cells. All of these ideas, both individually and collectively, caused students to modify or even redesign part of their model to fit the evidence they were seeing and experiencing. Exploration and application of their model to a range of phenomena provided opportunities for complex problem solving and persistence in obtaining a solution.

Helen's model differs from student models that are constructed in typical science classrooms. In particular, she has to develop an ontology for the model, and creatively constructs theoretical objects of little men and houses, along with constructing the properties for these entities. To explain light and color, a student might use traditional science entities such as photons, molecules, etc. What makes Helen's model unique is that she avoided traditional scientific terms in favor of invented objects that she could design and create properties and activities for. The use of invented theoretical objects created a playful environment that allowed for more open exploration of ideas, where the students did not fear being wrong about the terminology. Because the model was open-ended and created from theoretical objects like little men and houses, students were able to experiment, use playful analogies, and develop rich scientific theories about light and color.

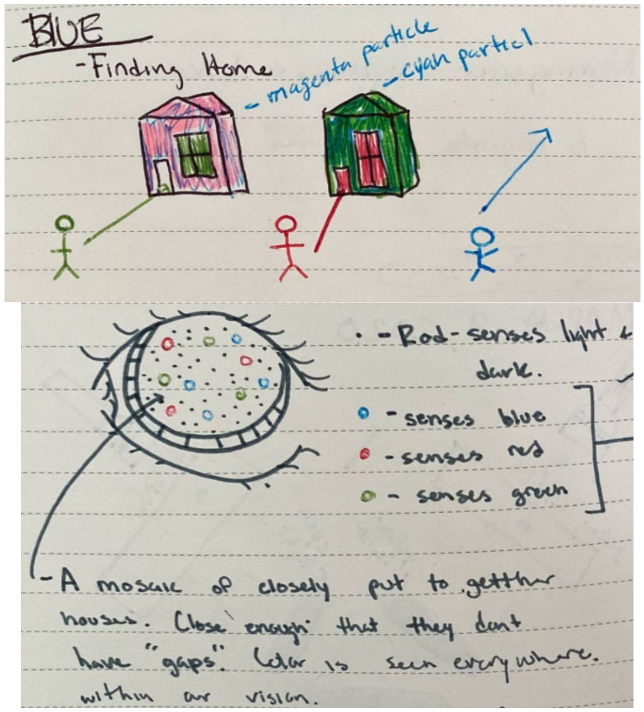

Figure 4 Photo from Notebook Showing Two Iterations of Helen's Model
Photos showing two different iterations of Helen's little man and house model to explain light and color. Top- Evolution of the model to include little men and houses, specifically looking at magenta and cyan filters. Bottom- Beginning to map little men and houses onto color perception of the human eye.

Elements of Tinkering

Because the students used novel theoretical objects as the entities in their model, they necessarily had to invent these entities and decide the types of action or activities that these entities do. This is to say, the students had to determine what colors little men could be, what colors houses could be, and how in different color combinations little men and houses interact. The process of designing the model, the little men, and the houses set the stage for the student to be able to 'tinker' as they developed their model, and grapple in authentic scientific inquiry. In this section, I look at the implications of this model building, and how the design of the model provides evidence of students tinkering with theoretical objects.

For the purpose of this study and drawing on work by Quan and Gupta (2020), Resnick and Rosenbaum (2013), and Vossoughi and Bevan (2014), I define tinkering as an iterative activity that has shifting goals, a playful disposition, and allows students to improvise. In the second round of coding, selected codes were chosen based on this definition of tinkering, and common themes seen in the literature. The four selected codes being; iteration, playfulness, shifting goals, and improvisation (Table 2). I apply these selected codes to the transcripts of the class discussion to look for evidence of tinkering in student talk. The implications of using these codes with a class discussion is to see if these elements of tinkering are present within the discussion, to say that students were engaging in the process of tinkering.

Playfulness

The first element of tinkering I looked for was playfulness. The element of playfulness is important for setting the tone of the discussion, allowing students to engage with ideas and present novel solutions. Playfulness often emerges in the analogies that students make, and the way that students use analogies to clarify ideas about their model. In the following transcript students are pondering what makes a house a house, and how different colored houses are different from one another. In this transcript, the playful orientation and interesting use of analogy is clear and helps show how playfulness plays a role in providing students the opportunities to tinker with their model and theoretical objects.

Helen: I have a question… So what makes a magenta house a magenta house, a yellow house a yellow house, and a green house a green house. They're different things…

George: I think you could say the houses that make up the magenta are, you could say slightly different... they have their own property of which, when you

	shoot light through it, it will emit this color because of the chemical property that makes it up, is what I think. And I may very well be wrong.
Instructor:	A house then has a profile for reds, greens and blues. It's not like a green house, blue house or a red house?
George:	Yes.
Instructor:	I see. It's a really nice house, so it's mostly going to say no to the teenagers who want to live there, but for the senior citizens it's okay?
Sarah:	It's a neighborhood association...
George:	Green is a college apartment complex, magenta is a 55-and-older, and blue is a suburb….
Helen:	I think I agree. I think I have that represented in my model. Kind of, but not super. I was more like, "This is what happens to each color." But I'm still saying that something different is happening with each of them.

In this brief excerpt, Helen proposes a question related to her model in which the students begin pondering what makes different colored houses look different. In asking this question, Helen is trying to refine her model and design the different entities (the houses and little men) to match the evidence she is seeing in the world with the gel filters. One student, George, attempts to answer Helen's questions by using technical terms such as 'emit' and 'chemical property'. But it is only when the question is revoiced using Helen's language of houses and little men that George's idea takes hold. To clarify George's idea further, Sarah suggests that maybe each different colored house is like a "neighborhood association", which George elaborates on by classifying each color into its own type of neighborhood (suburbs, apartment complex, etc.). The work that students are doing here is important for the design of their model. Through these analogies of neighborhoods and houses, students are able to determine that each color of house is different, while they are developing a plausible mechanism to explain these differences. By identifying this mechanism, students are able to improve their model and ensure that the model matches the real-world phenomena (Figure 5).

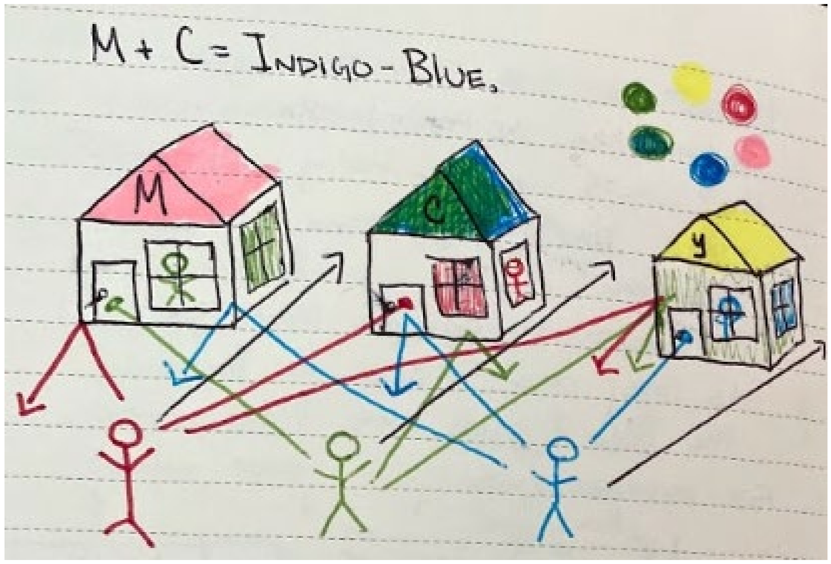

Figure 5 Photo from Student Notebook Showing Little Men Entering Houses
Drawing from a student's notebook showing little men and house model of light and color, where red, blue, and green little men enter magenta, cyan, and yellow houses as a way of explaining how printer inks and computer pixels can make 'all' the colors we see.

Playfulness is evident here by the use of 'fun' analogies and suggestions that students use to experiment with their model, and with the theoretical objects that comprise their model. For example, Sarah suggests that different colored houses could be different "neighborhood associations", and George elaborates on this idea by providing the analogy that "green is a college apartment complex, magenta is a 55-and-older [community]...". These comments show a playful nature because students are playing with ideas and suggesting fun analogies that could reconcile a problem within their model, but still fit with reality (i.e., we see different neighborhood associations like those suggested by the students). The playfulness also permeates throughout the conversation and is often the ingredient that allows students to experiment with seemingly unrelated ideas in order to make their model more coherent and identify key points in the mechanism.

The transcripts and class conversations are not the only place where students show this playful orientation, it is also evident in student notebooks (Figure 6). One student, Helen, shows her excitement and playfulness by recording key moments of intrigue in her notebook. After collecting ImageJ data that shows a particularly exciting result, she says " Im so excited" (Figure 6, left). This example shows playfulness because the student is recording her playful affect during moments when her research brings her excitement. Helen also records observations in a playful way, such as her entry of "mirrors are weird!" when the students were considering how mirrors would work in terms of their model. This observation is playful in nature because Helen adds emphasis (e.g., the exclamation point) and uses the term weird (more playful) instead of more typical science terms such as peculiar or giving a description of what makes them weird. The playfulness seen in Helen's notebook allows her to more fully explore ideas, gain more from empirical data, and tinker with her model of little men and houses.

Figure 6 Photo from Student Notebook Showing Playful Phrases
Left- Photo from a student's notebook showing the student's playful orientation when they explain their excitement based on data they have collected. Right- Photo from a student's notebook showing an entry where the student observed a 'weird' phenomenon within the context of the student's model.

Shifting Goals

From the transcript above where students are trying out different ideas for the mechanism of their model, along with playfulness, there are also shifting goals indicating moments of tinkering. Before this section of the transcript begins, students are discussing other topics including empirical evidence that was received from ImageJ analysis. It is when Helen asks the question at the beginning of this exchange that the goals of the group shift, and all students become focused on determining the mechanism for different colored houses. This was a common occurrence throughout the semester with this group of students, where one student would pose a question and the students would collectively work on solving the problem for that question. However, many questions were born from prior questions where students would often interject new questions in the middle of conversations, thus shifting the goal of the group, and the model. This ability to shift goals, try out new ideas, and modify their model based on solutions shows how students were able to tinker from moment-to-moment with their model and theoretical objects.

Although this exchange in the first transcript is brief, all four elements of tinkering are present in the exchange between students. First, the way the students engage with the ideas of houses, and the analogies they use come across as playful, and create an overall sense of playfulness throughout the conversation. There is also a clear shift in goals, as Helen interjects her question about houses at the beginning of this conversation which changes the topic of the conversation and establishes a new goal for the group to grapple with. The idea of the 'neighborhood association' and houses of different colors being different neighborhoods is improvisational as it avoids technical scientific language but still explains the underlying scientific concept. The neighborhood association analogy is also improvisational because it was a random analogy introduced to explain an idea and provide a possible solution to the problem of what makes houses different. Finally, this exchange is iterative, as students propose multiple ideas of what makes houses different. The properties that houses have in the model is highly iterative and becomes a topic of discussion several times over the course of the class session, as students work to identify how houses are different based on color, how houses interact with little men, and how house color changes the interaction between little men and houses. With all four elements present in this exchange, I suggest that the students are engaging in the process of tinkering. Although they may not be manipulating tangible artifacts as traditional tinkering would suggest, the students are still manipulating, refining, prototyping and testing theoretical objects in a form of 'idea tinkering' as they design their model of light and color.

Iteration

Perhaps the most difficult element of tinkering to identify in moment-to-moment coding was iteration. Iteration is a process that occurs over time, instead of one particular instance. Because of the difficult nature of identifying iteration in a singular moment the transcript as a whole was analyzed for iterative topics. One topic that emerged was the idea of 'user error' or the idea that the brain makes an error and 'sees' one color when there are really two colors present (Figure 7). Students come back to this idea of user error over and over again until they finally reach a consensus at the end of class session on how to define user error and the implications for their model. In the following transcript is a short example of the students' discussion on user error.

Sarah:	I think you guys are just saying that you don't like the name of user error. I don't know, I just chose it because it's [the perceived color] not describing what is actually happening.
Helen:	But it is describing what's happening. It's not like we're looking at something that has blue and green light and we're only seeing green or blue. We're seeing both, they're just in a different form.
Sarah:	What if I showed you a Christmas tree with red ornaments and you're like, "That's brown." And I would be like, "It's pretty clearly red and green".

In this discussion, students decide that magenta little men could not exist and instead the color of magenta is created when green men are 'eaten or consumed' by magenta houses leaving behind red and blue little men to create the magenta color that we perceive. It was this determination that magenta is composed of two different types of little men that led one student to suggest that this was 'user error', as in an error in the way that we see one color when there are two colors present (Figure 7). This was not a new idea, as the students had also grappled with yellow (made of red and green) and cyan (made of blue and green) being 'user error', but this was the first instance where the students intentionally set out to define what 'user error' means in terms of their model. While the goal of this conversation was not to build theory or clarify understanding, the use of analogy and moreover, tinkering with theoretical objects ("user error" colors, little men, and houses) provided an opportunity for deeper sensemaking of the mechanism that causes certain colors like magenta. Tinkering with theoretical objects, then, can be a vehicle through which students come to understand complex scientific processes.

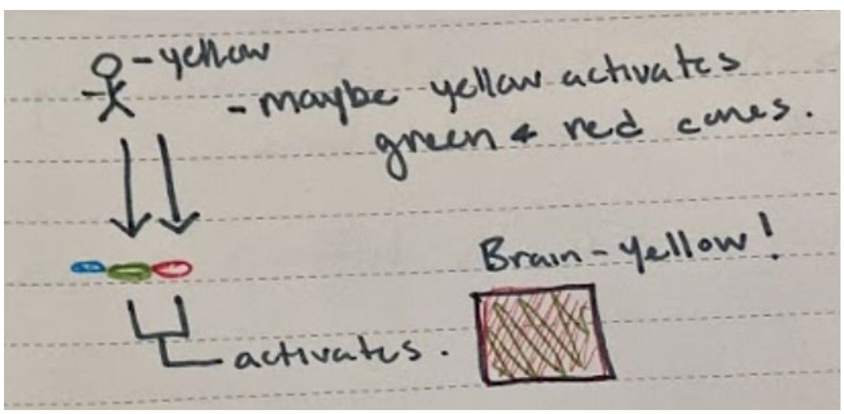

Figure 7 Drawing from Student Notebook Showing 'User Error'
Photo from student's notebook showing 'user error' with the color yellow. Here a yellow little man is seen, then the yellow activates green and red cones in the eye (seen as the green and red circles), finally, the brain perceives the combination of green and red cones as yellow, thus 'user error'.

In this exchange, again there are elements of tinkering with theoretical objects. As students focused on this topic of 'user error' multiple times over the course of the class period, ‘user error’ as an idea had many iterations, until they reached the conclusion and final consensus on a definition in the exchange seen above. Students suggested ‘user error’ with other colors such as cyan and yellow, and even thought about more complex colors like brown, black, and white which are composed of many different types of ‘little men’. One student suggested that these colors, cyan, magenta, and yellow, were not composed of more than one color and instead came in a ‘pure’ form so therefore there could be such a thing as ‘user error’. Finally, students collect empirical data (using ImageJ) showing how a computer screen makes yellow from the combination of red and green pixels. It is this data that leads students to believe that ‘user error’ is possible and must be accounted for in their model. Sarah tries to explain this idea by using the Christmas tree analogy where seeing ‘user error’ would be looking at the tree and seeing the ornaments as one color (brown in this case), instead of being able to separate the colors (red and green). It is over many iterations of the same idea of ‘user error’ that students are able to constructively argue and ultimately create a more coherent model from reaching a consensus. The tinkering seen here allowed students to playfully experiment with ideas, hedge bets on who was right, and lead to a more complete picture of the phenomenon being studied.

Improvisation

From the second transcript above, along with iteration of ideas, we also see improvisation with the use of analogy. The use of the term ‘user error’ is itself an improvisational tool that Sarah suggested to describe a particular phenomenon that the students kept witnessing over and over. The problem with the improvisation of ‘user error’ is that once the term was suggested, it then had to be defined by the group and reconciled in terms of the students' model. Of course, the students did reach a consensus on what was meant by 'user error' and the ideas became an integral part of their model especially when they needed to explain how the eye sees colors. Another improvisational move was the use of analogy, particularly with the Christmas tree example. To explain 'user error' further, Sarah suggests that these 'user error' colors (cyan, magenta, and yellow) are not changing form but rather our brain changes how we see them. This is explained through the use of a Christmas tree analogy where we are seeing red and green on the tree and are not experiencing 'user error' by seeing a mixture of these colors as brown. The improvisation of the Christmas tree analogy allows for further development of the idea of 'user error' and provides a platform or "foothold idea" (Hammer & van Zee, 2006, p. 26-27) for students to use to sense make as a group to reach a consensus on what 'user error' means to them. In this sense, improvisation is a vital part of tinkering as it allows students to suggest ideas, creates a space for those ideas to be taken seriously, and provides uptake of the final idea in students' model.

Along with improvisation and iteration, there is also the inherent playfulness that is evident in conversation from the second transcript above, with students coining the term 'user error' to explain the phenomenon that they are seeing to the use of Christmas trees to explain their thinking and clarify flaws in their model. Finally, because the student continuously switched between discussing the properties of houses and little men and the idea of 'user error', it can be said that there was a shift in goals within the conversation. It is important to note that although goals did shift there was still a clear resolution of the problem where a consensus was reached on the definition of 'user error' seen in the exchange above. In turn, when students tinker with theoretical objects it offers the opportunity to design models and make sense of complex science ideas in a collaborative setting.

Case 2: Pacmen and BBs

Case Boundaries

The second case of this study occurred during the Spring 2022, from January to May of 2022. This semester of STEM-ED 350: Research Methods consisted of six students, but only five agreed to participate in research. The class sessions were structured the same as in the previous case, and the class met twice a week for 75-minute class sessions. Students also focused on the topic of light and color, however, this case started with pinhole cameras as their first phenomena of light and color before moving on to the "Is every color in the rainbow?" question. Even though this case occurred during the COVID-19 pandemic, all class sessions were able to occur in-person which greatly increased the collaboration among the students and the development of their model. However, students were required to have assigned seating and remain socially distanced, which impacted the sense of community and collaboration within the course. Class sessions started out being videotaped, but halfway through the semester recording switched to audio taping of class conversations to accommodate the discomfort with the video camera that a student experienced. Student notebooks were also obtained and photographed as data, along with photos of class experiments and physical material designs. Transcripts from video/audio recordings along with photographs of student notebooks were the two main sources of data for this case study and will be used to explore student model building and tinkering with ideas. A specific transcript of a class conversation and entries from student notebooks will be highlighted to construct the timeline of the students' model and show how students are able to tinker with their model and theoretical objects.

Timeline

Students in this case began the semester by building and exploring the phenomena of the pinhole camera (Figure 8). They started the semester by building their own personal pinhole camera out of cardboard boxes, duct tape, aluminum foil and construction paper. Then, students took their pinhole cameras outside where they could see the world upside down inside their pinhole camera. After experiencing this initial phenomenon, students spent several weeks collaborating to figure out the mechanism that allows the camera to work. Students would begin the process of inventing theoretical objects, some of which would become a major part of their model of light and color. After getting a good grasp of the mechanism behind the pinhole camera, students moved on to explore the "Is every color in the rainbow?" question. Students used ideas about light that they constructed during the pinhole camera phase of the class and built upon these ideas to begin piecing together a novel mechanistic model of light and color.

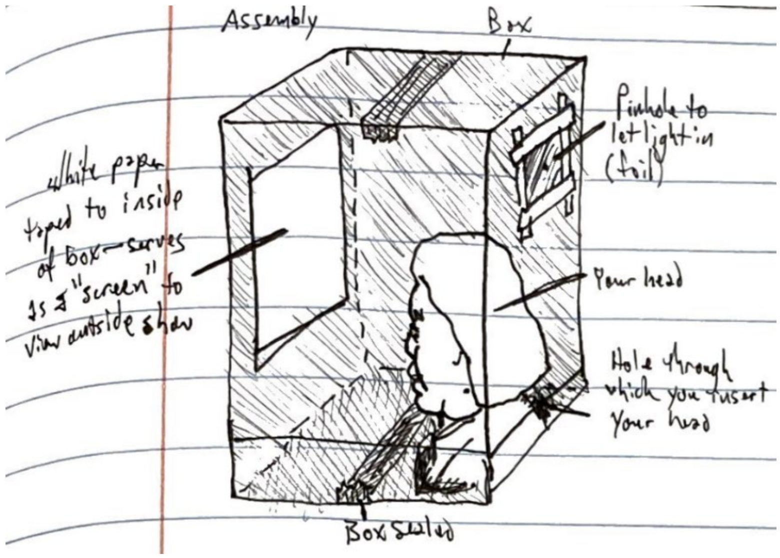

Figure 8 Student Drawing of a Pinhole Camera
Drawing from a student's notebook showing a pinhole camera. The student describes how the pinhole in the foil lets light into the box, and how the white paper acts as a screen to view the outside world.

Pinhole cameras are a simple but fascinating phenomenon to get students interested in light and color. The small hole in the back of the 'camera' allows light to reach the 'screen' (white construction paper) where the image of the world behind the camera can be seen (Figure 8). Students are often puzzled that there is any image at all; in addition, they are puzzled by: 1) the image being in color and not black and white; 2) that the image is upside down, and 3) that the larger the pinhole becomes, the blurrier the image. When constructing a model of how the pinhole camera works, students often have to account for these observations.

In the students' pursuit to understand the pinhole camera, they had to invent theoretical objects to explain how light can travel from outside the box and create the image on the screen. Students experimented with objects like 'poms poms' and 'bbs' to explain light particles. There was also disagreement whether the light was traveling in waves or as particles, so students would go back and forth between these ideas in their language. The main question that students used to determine the mechanism of the pinhole camera was, “Why, when the pinhole is larger, is the image blurry/fuzzy?” In exploring this question, students were able to create a model that shows how more light (larger pinhole) creates a blurry image due to many points of light from outside the box converging on the screen (Figure 9). Students also noticed that the image flips, so that it appears upside down on the screen. This was something that was addressed early in their model and remained consistent throughout their exploration of the pinhole camera. After several weeks, students were able to reach a consensus about why blurriness occurs with a larger pinhole and apply this knowledge to their model. Students would go on to use the knowledge they constructed from the pinhole camera to further explore light and color and develop a model for the rainbow question (“is every color in the rainbow?”).

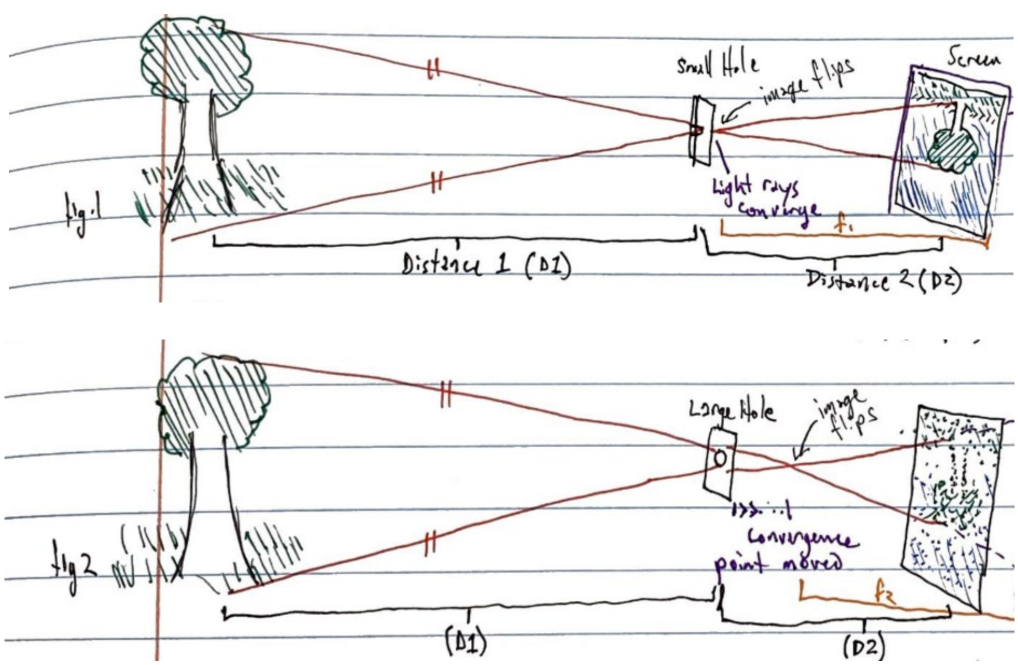

Figure 9 Student Drawing of How Blurry Image is Created in Pinhole Camera Student’s drawing showing the difference in image quality (not blurry vs blurry) based on the size of the pinhole. Top image shows how a small pinhole creates a clear and crisp image on the screen. Bottom image shows how a large pinhole creates an indistinct blurry image on the screen. Both drawings also show how the object of the image gets flipped when passing through the pinhole.

After constructing a mechanistic model to explain the pinhole camera, students moved on to think about if every color is in the rainbow, with the ultimate goal of having students develop a novel mechanistic model of light and color that could be applied to a range of phenomena. While working on a model of the pinhole camera, students invented a range of objects to describe light particles including pixels (to describe light as tiny dots flying through the air), ghost pixels (to capture how this light can pass through other pixels of light), pom poms (to describe light's reflection in all directions), yarn light (streams of light), and bbs (to describe light as so tiny it doesn't interact with other light, as an alternative to ghost pixels). Moving on to explore the rainbow question, students had to decide what term they would use to describe light particles and reached a consensus that the light could be modeled as traveling in particles and not waves. Students decided to use the term 'bb' to describe a light particle and further developed this theoretical object by saying that 'bb's' come in different colors, and these colors compose white light. Students would examine gel filters (Figure 2, left) and printer inks to determine how these tangible colored objects could provide empirical evidence to help them develop their model.

While looking at gel filters and printer inks, students discovered that they needed to invent an object for their model that could explain how light (bbs) interacts with inks and gels to exhibit their unique colors. They decided to call these objects 'pacmen' as they were eating the 'bbs' (light particles) that interacted with them to produce a color. For example, in yellow printer ink, which is composed of yellow pacmen, all colors of bbs interact with the ink, but the yellow pacmen eat all of the colors aside from red, green, and 'pure' yellow bbs to produce the yellow color that we see (Figure 10).

Through empirical evidence students were able to determine that bbs come in ‘pure’ forms and artificial forms. Pure yellow would be a bb that is ‘just’ yellow (such as one emitted from a sodium lamp), while an artificial yellow is one that is made from a combination of colors such as yellow created by red and green (like the pixels in a computer screen). The creation and refinement of pacmen, and the activities that pacmen were able to perform, was an integral part of developing the students' model and allowing them to construct a working mechanism of light and color.

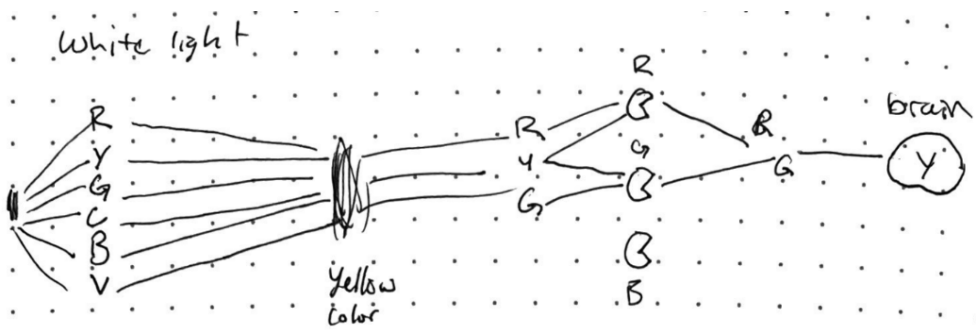

Figure 10 Student Drawing of Pacmen and BB Model
Drawing from a student’s notebook showing how the different colored bb’s in white light interact with a yellow object, and the pacmen in the object allow red, green, and ‘pure’ yellow bbs through so our brain perceives the object as yellow.

Creating the theoretical object of pacmen allowed students to apply their model to how the eye perceives color. In exploring color vision, the students realized that they needed to modify their pacmen model slightly to accommodate for the fact that the cone cells in the eye do a particular thing to bbs (light particles). Unlike the pacmen in ink, which converts bbs to heat, cone cells absorb the light and convert it to a signal that is sent to the brain. Recognizing how cone cells are different from dye particles, the students created “packaging pacmen” to represent the cone cells in the eye. Packaging pacmen, therefore, only come in red, green, and blue as these are the long, medium, and short wavelength colors that our cone cells recognize. Packaging pacmen are different from regular pacmen (dye particles) because they only come in these three colors, and they are able to 'eat' bbs and translate a message to the brain. Figure 11 shows the complete pacmen and bb model, including packaging pacmen, that the students created. In Figure 11, all colored bbs are present in white light, these bbs then interact with the yellow ink containing pacmen, the pacmen eat the bbs that are not required to produce the color yellow, and the bbs that do create the perception of yellow (red, green, and 'pure' yellow) are reflected to the eye, where the red and green packaging pacmen in the eye eat these bbs and translate to the brain that it has seen yellow (Figure 11).

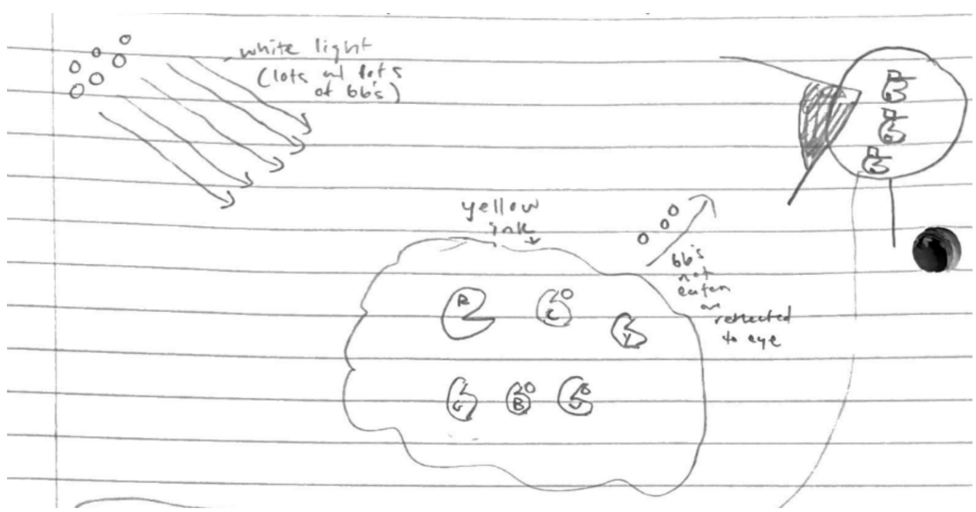

Figure 11 Student Drawing of Color Vision with Pacmen, BBs, and Packaging Pacmen

Photo from student's notebook showing the complete pacmen and bb model of light and color. In the drawing, bbs in white light interact with the yellow ink. Pacmen in the yellow ink eat all non-yellow bbs (every bb but red, green, and 'pure' yellow). The bbs that comprise yellow are then reflected to the eye, where the red and green packaging pacmen are triggered telling the brain that it has seen yellow.

Over the course of the semester, students were able to grapple with the complex scientific problems around light and color, and in turn, were able to design a novel mechanistic model that could be applied to a range of phenomena. In order to fully grasp the depth of light and color, students had to invent theoretical objects to explain light particles, dye particles, and cone cells. The creation of the pacmen and bb model allowed students to apply their model to a wide range of topics such as global warming, photosynthesis, color blindness, printer inks, oil slicks, and gel filters. The invention of theoretical objects and the model itself also allowed students to tinker, try out theories, and develop new knowledge on the topic. In the next section, I outline how students tinkered with their pacman and bb model, and how the act of tinkering aided in the construction of the model itself.

Elements of Tinkering

As students explore various topics of light and color, they build models that require things like light particles, dye particles, and cone cells, and therefore must invent these things as theoretical objects in their model. In this case, students use the objects of pacmen (dye particles) and bbs (light particles) to represent these ideas and it is in deciding what these theoretical objects can do that tinkering occurs. Students must decide to call light particles ‘bbs’, then determine what colors these ‘bbs’ can be. They must work out what a pacman is, what kind of bbs it can eat and how it changes when it becomes a packaging pacman. Using a transcript of a rich class conversation along with examples from student notebooks, I will show how students are tinkering with their model and theoretical objects. The playful iterative process of refining their model closely resembles the activity of tinkering. In this section, I will examine the different elements of tinkering and show how students are engaging in tinkering with their model and objects.

Playfulness

In examining the transcript, the first element of tinkering that emerged was playfulness. Playfulness is often seen in the use of analogy and in the orientation of the students and ideas. Having a discussion that accommodates for playfulness allows students to experiment ideas and create novel representations in their models. In the transcript that follows students are grappling with the idea of glow-in-the-dark. They decide that glow-in-the-dark objects must be doing something special to bbs, and therefore one student, Irene, suggests that pacmen must 'puke' and this produces the glow-in-the-dark effect.

Instructor:	What does a glow-in-the-dark Pac-Man eat?
Irene:	I said that they eat everything, but then they decide to puke up some stuff.
Instructor:	What do they puke up?
Irene:	Well, it looks like the green. It's kind of green color[ed].
Instructor:	Curious what others think of that. Or do you want to say more about how you've come to the "Eat everything, puke some things"?
Irene:	We can't tell if they're glowing because it's light out. So does it get to a point where they would? Okay, if it lasts up to four hours, if they're in the sun for... I don't know. When would they start puking up stuff? Just because we can't see it, it doesn't mean that they aren't…
Instructor:	Here's what I would picture. It's like stars are out during the day, but we don't see them because the sun is too bright. Other thoughts?
Felix:	I was thinking about the bioluminescent organisms in the ocean where there's no sunlight that gets to them because they're so deep down in the water. But they're still able to produce light, basically, luminescence. That's why I started thinking more of... They're more of a source, like an ignition source.

In this excerpt, students are experimenting with their modeling to determine how their model might accommodate for glow-in-the-dark. The instructor begins the conversation by asking students what a glow-in-the-dark pacman eats. This suggests to students that it is time to tinker with their model in pursuit of a puzzling question. It also gets students to think about how glow-in-the-dark objects have to have glow-in-the-dark pacmen in them, and how these objects must be doing something different (than regular pacmen) to produce the glow-in-the-dark effect. One student, Irene, then suggests that the pacmen eat everything (all bbs), but 'puke' up some bbs to cause glow-in-the-dark. When asked what these glow-in-the-dark pacmen must puke up, Irene responds that it is "green-ish" based on her prior knowledge of glow-in-the-dark objects. When asked to explain how these pacmen are able to eat everything but puke up some things, Irene explains that it is due to 'brightness', so the glow-in-the-dark pacmen are always puking, but we can only see them doing this activity when it is dark. The instructor compares this to the way that we only see stars at night, or the sun during the day. Finally, one student, Felix, suggests that maybe the mechanism is not puking, but rather a similar process to bioluminescence as seen in biology. Through the exploration of these ideas, students are able to tinker with pacmen and their model to suggest mechanisms that could explain glow-in-the-dark.

This excerpt is clear evidence of playfulness in the use of analogy and the refinement of activities that pacmen are permitted to do. Having a theoretical object in a model that can 'puke' up other theoretical objects (bbs) is inherently playful and shows how creative and productive the tinker space can be for model development. The personification of the pacmen to be able to puke is playful because it allows for possibilities where pacmen are able to do almost anything and be also anything. In fact, we see many versions of pacmen over the course of the students' model from regular pacmen, to packaging pacmen in the eye, to puking pacmen. As the students' model encounters different phenomena, it is often the pacmen that are modified to fit the phenomena, and it is the ability to play and be playful that makes this possible.

The playful orientation of the conversation also plays an essential role in allowing students to tinker. Playfulness creates a space where all ideas are taken seriously, as seen here with the students' careful consideration of what it means for their model if pacmen could puke. A playful orientation also provides access for all students to express their ideas, concerns, and suggest alternatives which occurs over the course of the class conversation. Therefore, playfulness is a crucial component to allow students to tinker with ideas and construct mechanistic models.

Shifting Goals

From the excerpt of the transcript above, along with playfulness, there is also evidence of shifting goals. Most of the excerpt highlights Irene's idea that the effect of glow-in-the-dark is produced by pacman puking, however, at the end, Felix suggests a different mechanism for glow-in-the-dark. Felix suggests that glow-in-the-dark occurs naturally like bioluminescence; this suggestion emerges from Felix's prior knowledge in biology with bioluminescent fungi and bacteria. This sudden change from one mechanism to another shows a shift in goals while students decipher which mechanism seems like a better fit for their model and their prior knowledge. This quick shift between various goals allows students to tinker with a range of ideas quickly before settling on the one that is most applicable to their model and the phenomena.

Besides playfulness and shifting goals, this excerpt also showcases the other elements of tinkering. Iteration is present in the way Irene begins by modifying the pacmen, and then returns to puking pacmen and refines the action they are able to take in the model. Improvisation is present in the suggestion of puking pacmen. The student, Irene, was looking for a way to describe what she was seeing with glow-in-the-dark and therefore retrofitted a common real-world activity of puking to accommodate for what she was seeing and what the model (specifically pacmen) could do. Felix also improvises by suggesting bioluminescence as a mechanism. He maps his prior knowledge onto what he is seeing and adjusts the model accordingly. With these four elements of tinkering present, it shows how spaces that allow for tinkering are cognitively rich, creative, and spur development of novel mechanistic models.

Iteration

Looking for and diagnosing iteration in a transcript, or even an excerpt can be quite difficult as iteration occurs over time. This being said, the class discussion of puking pacmen led to many moments of iteration as students returned to the mechanism of puking pacmen over and over again. In the excerpt that follows, students have returned to the idea of puking pacmen, and are once again thinking through the mechanism that creates glow-in-the-dark. In this transcript, students think about glow-in-the-dark colors, and then consider what other things they have encountered that glow-in-the-dark (like, neon bracelets and ultraviolet lights). In exploring these ideas students are able to engage in iteration and tinker with their model to refine their theoretical objects of pacmen.

Instructor: Yeah. The picture I showed you was definitely a white-ish green, wasn't it?

Irene: Puke up some green-ish.

Sofia: There's other colors for glow-in-the-dark bracelets. You can get pink, you can get orange. I think you can get yellow. There's other neon colors you can get. But those are different because you don't have to have it sit in the light. You can just break it. You just have to just break it and it's neon.

Felix: And it's not just white though, right? For crime scenes, they'll use ultraviolet to find all sorts of different things.

Sofia: Yeah, but I just can't remember which colors you could see, what we're reflecting. What kind of neon colors you can see?

Christina: Feel like anything that was more brighter than black usually reflected off to some degree, but it's like the darker your colors got, the more you were hidden.

In this excerpt, students, who began by modifying pacmen to create "puking pacmen", have returned to the idea of puking pacmen and are discussing the colors in which objects glow and the methods that people use to produce glow-in-the-dark. After showing the students a picture of a ceiling glow-in-the-dark star, the students begin discussing what colors the pacmen would puke up to produce this color. Irene suggests that the pacmen would puke up a "green-ish" color since that is the color commonly seen with glow-in-the-dark objects. Another student, Sofia, suggests that glow-in-the-dark comes in other colors such as pink, orange and yellow based on prior knowledge of using the snap and glow bracelets as a kid. Sofia goes on to explain that the mechanism for these bracelets might be different because they do not require light like the glow-in-the-dark stars do (in fact, the bracelets are a chemical reaction). Felix jumps into the conversation to have the group consider ultraviolet light and think about if this is different from the neon colors seen with the bracelets. Sofia asks what neon colors can you see with a black light, elaborating on Felix's suggestion of ultraviolet light. Finally, Christina mentions that any color that is not black would be visible "to some degree" in ultraviolet. Over the course of this conversation, students are modifying their theoretical objects of pacmen and try to work out what colors glow-in-the-dark pacmen would be, thus refining their model and theoretical objects.

This exchange shows iteration as students return to the idea of puking pacmen multiple times over the course of the class session. Students determining what pacmen eat and puke to produce glow-in-the-dark is an example of students tinkering with both their theoretical objects and their model. Iteration is an important part of students' development of their model and refinement of their theoretical objects. The ability to tinker allows students to revisit ideas, like puking pacmen over and over, until collectively the students can decide the best fit for the phenomenon and their model. In this respect, iteration through tinker is an essential part of model construction and provides a ‘low-stakes’ environment for experimentation.

Perhaps the idea that was iterated the most during the course, was the idea that the larger the pinhole the blurrier the image. Over several weeks, the students returned to this idea in the pursuit of figuring out what causes the blurriness. First, students had to decide that the light was traveling in particles and not waves. Then students thought that perhaps portions of the image were overlapping (like circles) to create the blurriness. Other students thought that two separate images were being created and when not perfectly aligned they create blurriness on the screen. Finally, one student created a physical model, using binders, tape, yarn, and aluminum foil (Figure 12), to show how multiple points of light are coming from the physical object but end up in different places on the screen creating this blurry image. This idea became the consensus of the class, but only after many iterations of other ideas and models. By being able to iterate and explore every idea, students were able to construct a novel mechanism model that clearly shows the phenomenon of why a larger pinhole would create a blurry image.

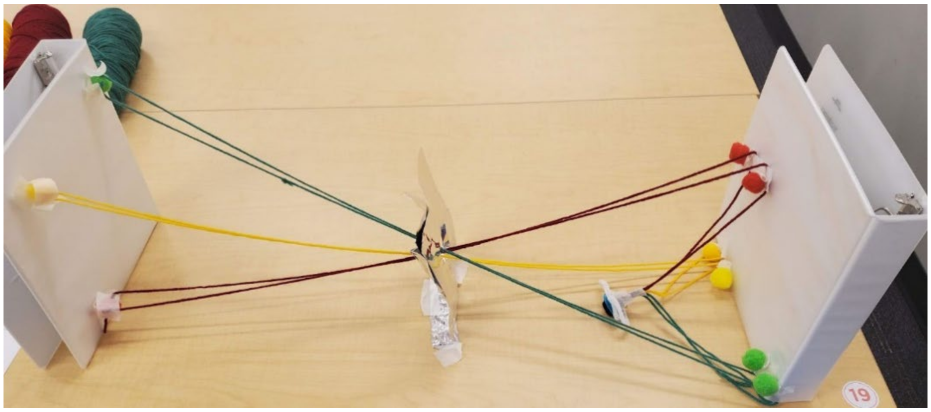

Figure 12 Photo of Student’s Model of Blurriness in a Pinhole Camera
Photograph showing a student's model of why a larger pinhole creates a blurry image. The model is made from craft pom poms, binders, tape, yarn, and aluminum foil. In this model, the pom poms represent a single point of light, the yarn represents the path that the pom poms travel from the physical object to the screen, the aluminum foil represents the hole of the pinhole camera through which the pom poms will travel, and the binders represent the object outside of the camera along with the white screen inside the camera. This model shows that multiple points of light from the same source on the objects travel through the larger pinhole thus creating a blurry image on the screen.

The idea of pacman is itself an iteration that students would revisit often throughout model development. Pacman started as a way to describe dye molecules in printer inks and gel filters. They become the theoretical objects inside of things that ‘eat’ bbs to produce color. When students encountered color vision, pacmen morphed into packaging pacman as a way to explain the cone cells in our eyes, and packaging pacmen would become a vital part of the students’ model. Pacmen changed again when students encountered glow-in-the-dark, as seen in the transcripts above. As students continued to apply their model to more topics of light and color, pacmen were often the first piece of the model that was adapted. This iteration in pacmen over the development of the model shows how students are able to construct emergent solutions to a range of scientific problems. Also, the ability to change theoretical objects, as students changed the pacemen in this model, is a quality indicative and inherent to tinkering.

Improvisation

Along with iterative development, students also engage in improvisational ideas in the transcript above. Students use analogies and prior knowledge to suggest mechanisms for glow-in-the-dark and these analogies are improvisational. The first suggestion that the pacmen can puke is improvisational as it takes a seemingly unrelated idea (puking) and applies it to the students' model. Students go on to discuss other objects that glow-in-the-dark including bracelets, ultraviolet lights, and glow-in-the-dark stars, all of which were improvised suggestions that happened to come up based on the conversation. Finally, Felix improvises by suggesting bioluminescence as an alternative mechanism to puking. Improvisation within tinkering spaces allows students to make novel suggestions and for these suggestions to be taken seriously. Without improvisation, puking pacmen may not have become the mechanism that students used to explain glow-in-the-dark objects. Improvisation provides a kind of epistemic agency and freedom for students to ponder and suggest ideas.

Besides improvisation and iteration, the second transcript above also exhibits other elements of tinkering. The idea of pacmen puking in neon colors is playful, and the various suggestions of crime scene black (ultraviolet) lights and neon bracelets shows the playful orientation of the conversation. There is also a constant shift in goals within this excerpt. First students are discussing the colors of the glow-in-the-dark stars, then the goal shifts to consider what other colors glow-in-the-dark things (like the bracelets) can be, and it shifts again to consider what colors look like they glow-in-the-dark in ultraviolet light. It becomes clear that students are tinkering with theoretical objects in this excerpt, and this tinkering provides an avenue for model development.

Cross Case Analysis

Similarities

In both cases, the activity of tinkering was essential in helping students invent theoretical objects as a means of developing a novel mechanistic model of light and color. Students in both cases were able to develop theoretical objects to explain light particles and dye particles, all of which would allow students to tinker and decipher the mechanism behind light and color phenomena. Both cases also exhibited all four elements of tinkering and showed how tinkering can play a major role in supporting mechanistic model building in the science classroom. Finally, both cases showed how novel models adapt over time as they encounter new phenomena, and how the development of a novel model allows students to explore a wider range of topics. Both modeling and tinkering are essential to the narrative of these case studies that show how these practices allow for constructive collaboration to develop novel mechanistic models in the science classroom.

Differences

Both cases in this study also experienced some fundamental differences that contributed to the production of students' models and ability for students to tinker. In the first case, one student created the little men and houses models, and this model was positively received and taken up by the class. The class persisted with this model for the duration of the semester but were not able to design a completed model that could account for all of their observations due to the onset of the COVID-19 pandemic. The second case, however, was able to fully develop and apply their pacmen and bbs model to a wide range of phenomena, not just explaining the original phenomenon, but applying it to novel cases. Unlike the first case, the second case struggled with reaching a consensus on what to call their theoretical objects and what activities these objects could do. For example, one student did not feel like the idea of packaging pacmen accurately represented the mechanism of the cone cells in the eye, and therefore wanted to represent cone cells as 'trampolines' that bbs bounced off to activate. Eventually, all students agreed to use packaging pacmen as the representation of cone cells, but only after extensive debate and collaboration. In fact, many weeks were spent discussing what the role of the bb was, what the role of the pacman was, and what kind of activities each of these entities could do. Students in the second case also started their semester by looking at the pinhole camera and constructing a mechanistic model of this phenomenon, while the first case jumped straight into the rainbow question. In addition, the second case could have gotten further with their model than the first case, because they got a practice run designing a model with pinhole cameras that the first case did not receive. Overall, despite any difference that these cases experienced, both cases were still able to construct novel mechanistic models of light and color through the iterative playful process of 'idea tinkering'.

Summary

Using a multiple case study approach, I examined two cases where students engaged in model building to describe the complex scientific phenomena of light and color via an activity I describe as "idea tinkering". Exploring transcripts of class conversations and student notebook data, I show how students tinker with models and theoretical objects. In designing a model, it becomes apparent that students must invent theoretical objects as the "players" in their model, which we saw here as pacmen, bbs, little men, and houses. The decomposition of tinkering into its four basic components (iteration, playfulness, improvisation, and shifting goals) provided evidence that tinkering is an essential activity in the development of novel models. With the data collected and analyzed here, it becomes clear that tinkering is a practice with great value in the science classroom.

CHAPTER FIVE: DISCUSSION AND CONCLUSION

In this study, I set out with the goal to define and investigate ‘idea tinkering’ in the context of model building in the science classroom. The goal of this study was to determine the role of tinkering in students’ construction of novel mechanistic models of light and color. In this section, I address how the results and data of this study answer my research question and sub questions. I then briefly describe the type of environment that is conducive for tinkering with models and theoretical objects. I look at the role of language in model building, and how language supports students’ epistemic agency and the creation and refinements of ontology. Finally, I draw conclusions on the study as a whole and discuss future research opportunities based on what was learned.

Addressing the Research Questions

For this study, I set out with the goal of answering one main research question and two sub-questions that emerged from the main question. Using data obtained in this study, I will address each question, and discuss the implications of the results for each question. Below, this section has been divided based on the research questions and ‘answers’ to each research question have been provided.

<u>Main Question: When students are developing models of scientific phenomena, is there evidence that their activity has parallels to 'tinkering' from engineering contexts?</u>

Based on the data collected in this study, there is evidence that students engage in tinkering activities during model development. For the purposes of this study, tinkering is defined as an iterative, playful process where improvisation is used and shifts in goals occur. This definition of tinkering is based on the four most common themes of tinkering seen in the literature. The data, specifically, transcripts of class discussions, were coded and analyzed using these four themes to look for evidence of tinkering. From the data, I was able to determine that students are engaging in all four elements of tinkering, both at individual times and collectively. That is to say, that students can have a conservation that is not just playful or just improvisational, but they can all have a conversation where they are playful, improvisational, iterative, and have shifting goals. Because tinkering is often a practice that unfolds over time it is difficult to identify tinkering in the moment-to-moment interactions of students, which is precisely why the data was examined across the entire semester-long case in addition to the shorter transcript excerpts. Based on the collective evidence presented here I argue that 'idea tinkering' is an activity that occurs during model building of science phenomena. Furthermore, novel model building seems to be an activity that inspires and sustains tinkering, though more research is needed.

Sub-question 1: How is tinkering with models similar/different from tinkering with physical artifacts?

Many similarities exist between tinkering with models and theoretical objects, as seen in this study, and tinkering with physical artifacts as typically seen in engineering contexts. First, both kinds of tinkering (tinkering with physical objects, and tinkering with theoretical objects) require the four elements of tinkering outlined in this study (e.g., playful, iterative, improvisational, and shifting goals). Tinkering spaces also exhibit the components outlined by Resnick and Rosenbaum (2013) of immediate feedback, fluid experimentation, and open exploration, all of which are seen in both tinkering with physical objects and tinkering with theoretical objects. Finally, both forms of tinkering encounter the mangle (Manz, 2015; Pickering, 1995) which causes tinkerers to adapt and change their design or goal. The mangle is often described as a resistance by materials, where the materials tell the designer, experimenter, or tinkerer that their original design will not work; nature “pushes back” and contributes to the alternation of the design (Manz, 2015). Though usually a physical phenomenon, the mangle is also something that can be seen with theoretical objects. For example, in Case 1, Helen creates her model of light and color using little men and fences. However, with further evidence and examination of gel filters, she soon realizes that she needs a different theoretical object to fully capture the mechanism of how the dye molecules ‘eat’ the light particles (little men), so she creates houses to replace fences. This example shows a student encountering the mangle as her model tells her that fences are not the right theoretical objects to describe the mechanism that is occurring. Overall, there is a wide range of similarities between physical tinkering and theoretical ‘idea’ tinkering, therefore tinkering with models and theoretical objects should be investigated further as an important practice to add to the science classroom.

While many similarities exist between these two forms of tinkering, there are also some critical differences that set them apart. Perhaps the biggest difference is the objects that are used in each form of tinkering. Tinkering with physical objects requires materials, a physical space, and the ability to manipulate those materials. On the other hand, tinkering with theoretical objects requires the ideas or theoretical objects, and in many cases, the invention of these theoretical objects. With the invention of theoretical objects comes the need to define these objects and determine the activities that these objects can engage in. This makes tinkering with theoretical objects more cognitively complex than physical tinkering (that it requires more knowledge construction and recall of prior experiences), but also makes tinkering with theoretical objects more creative and playful than physical tinkering (since students are designing these objects from 'scratch'). With far more similarities than differences, tinkering with models and theoretical objects is an activity that could sustain model building and lead to productive innovations.

Sub-question 2: What is the importance of these theoretical objects for tinkering and possibly modeling?

The invention and refinement of theoretical objects is important to help spur tinkering and sustain model building. The theoretical objects that students produce are important because they provide the playful, improvisational, and often iterative aspect that triggers tinkering with both the model as a whole, and the individual theoretical objects. This is seen especially in the production and refinement of pacmen. Pacmen as an idea is inherently playful, the idea was first suggested in an improvisational way, and the students returned to pacmen iteratively over the course of constructing their model. The invention of theoretical objects also lends itself to providing students with opportunities for epistemic agency (Miller et al., 2018). Students get choice and freedom to invent and design their theoretical objects, and models, in any way they see fit; this requires agency. The use of their models and theoretical objects to sensemake and build knowledge also requires epistemic agency. Therefore, theoretical objects are important to engage students in tinkering where they use agency to create novel models.

Additional Considerations

In addition to the research questions addressed above, two additional areas emerged during the study: the context in which tinkering emerges, and the role of language and ontology in tinkering. I describe these briefly below, noting that additional research is necessary to further develop these themes.

Examining an Environment for Tinkering

Tinkering is an activity that requires a particular environment that allows for exploration and iteration of ideas. Resnick and Rosenbaum (2013) identified three components that aid in the development of a space conducive to tinkering: immediate feedback, fluid experimentation, and open exploration. These components are seen throughout both cases of this study and create the opportunity for students to tinker with their models and theoretical objects. In this section, I will interpret the results in terms of these three components and discuss the implications of these components for tinkering in the science classroom.

The pursuit of coherency of a mechanistic model provides the perfect vehicle for students to receive 'immediate feedback' on their ideas and theories. In a physical context, this generally means being able to "run" the machine. In programming, tinkerers often see if the program compiles and runs; in a theoretical context, we think of students "running" their model and checking it against data or other known scientific facts (e.g., energy conservation or that black objects get hotter than white objects). So here, we look for whether or not students can rapidly test out their models and revise as needed. Students receive immediate feedback when they check ideas against their scientific knowledge. As students suggest an idea, they then must test this idea in their model, and against empirical data. The resulting decision to either reject the idea or integrate it into the model in the immediate feedback necessary for tinkering.

An example of immediate feedback occurred in Case 1 when students needed to test the idea of 'user error'. Students had empirical evidence from their analysis of gel filters and printer inks but had not yet reconciled how this data was going to fit into their model. Through the use of analogies like the Christmas Tree example (Case 1, Transcript 2) students were able to test their idea of 'user error' and receive immediate feedback telling them that printer ink colors (cyan, magenta, and yellow) are in fact 'user error' (two colors perceived as an entirely different color by the brain) and therefore, 'user error' should be included in their model. There was also immediate feedback in Case 2, when students were testing the idea of puking pacman for glow-in-the-dark objects. One student, Irene, suggested that pacmen eat everything (all bbs) and puke up some things to produce the glow-in-the-dark effect. This idea was quickly taken up by the other students and tested in the parameters of their model. The immediate feedback from their model told them that puking pacmen was possible, but that they had to determine what exactly the pacmen were eating and puking. (Eating "everything" is the equivalent of black, and glow-in-the-dark appears a greenish white when not in the dark.) In this example, immediate feedback was used to determine the mechanism of a new phenomenon (glow-in-the-dark). Immediate feedback is an important component of a tinkering environment as it allows for iteration and improvisation of ideas, both of which are core elements of tinkering (Quan & Gupta, 2020; Schön, 1987; Vossoughi et al., 2013). It is clear that students were able to use immediate feedback with their models to refine their ideas and determine the underlying mechanism.

Fluid experimentation is a process that also allows for iteration, improvisation, and often leads to shifts in emergent goals. Perhaps the best example of fluid experimentation comes from Case 2, as the students iteratively experiment with their theoretical objects of pacmen. After looking at gel filters students realized that they needed some way to represent the dye molecules within the gels. They settled on the idea of pacmen as dye molecules, since the molecules were 'eating' certain bbs of light to produce color. Pacmen then became a foothold idea (Hammer & van Zee, 2006) that would be refined and adopted over time. Using the foothold of pacmen, students were able to modify this idea to create packaging pacmen as cone cells in the eye, and puking pacmen to explain glow-in-the-dark. This example of the modification of pacmen over time shows fluid experimentation as students continuously experimented with pacmen and the activities that pacmen could do in their model. Fluid experimentation is somewhat inherent to novel model building as students need to continuously adapt the entities, and activities of those entities, as their model encounters emergent problems and phenomena. The opportunities for fluid experimentation also allow for iteration, improvisational, and shifting goals which is conducive to tinkering during model building.

The final component used for creating a space for tinkering is open exploration. Arguably, open exploration is the most essential component in creating a tinkering space as it allows for the crucial element of playfulness. Open exploration also provides the opportunity for epistemic agency (Miller et al., 2018) where students get to make meaningful contributions during the knowledge building activities of tinkering and modeling. Along with epistemic agency, open exploration also provides a rich space of ontological innovation (diSessa & Cobb, 2004) where students get to construct theoretical objects that allow them to participate in explaining the world (or more specifically light and color). Within the two cases, open exploration is seen in the construction of theoretical objects, little men and houses in Case 1, and pacmen and bbs in Case 2. It is also seen in the improvisational use of analogies such as a Christmas tree as ‘user error’, neighborhood associations as different colored houses (both from Case 1), puking pacmen as a mechanism for glow-in-the-dark, or the alternative mechanism of bioluminescence to explain glow-in-the-dark (both from Case 2). In all of these examples, students are using open exploration to develop theoretical objects, build knowledge of light and color, improvise with analogies, and display a playful orientation. Therefore, tinkering spaces require open exploration of ideas to construct novel mechanistic models as a knowledge building community.

By examining these three components required for a tinkering environment, it becomes clear that each component lends itself to creating a specific aspect that allows for tinkering. Immediate feedback gives students a way to ‘run’ their models, test ideas, and productively make progress toward a coherent mechanistic model (Hammer & van Zee, 2006). Fluid experimentation allows students to adopt foothold ideas and use these ideas to bootstrap along their model in pursuit of understanding the mechanism and applying their model to imaginative phenomena. Open exploration establishes a critical component of tinkering where students have epistemic agency and get to play with ideas creating new theoretical objects and using the improvisation of analogies to build knowledge and better understand their phenomenon. Creating an environment for tinkering requires a multifaceted approach where all three of these components are present and students are free to explore and create as a community in meaningful ways towards a shared goal.

Language and Ontology

The process of mechanistic modeling requires entities and activities (Russ et al., 2008); when creating novel mechanistic models, as seen in this study, those entities and the activities they can perform are frequently novel. Throughout this study we have seen students invent terms for the theoretical objects of their model (i.e., little men, houses, packaging pacmen, and bbs). I hypothesize that the invention of these new terms is not a coincidence, and that 'idea tinkering' and novel model building are activities that are uniquely suited to require students to invent terms. In addition, while these invented terms may seem like "everyday language" the way that the students use these terms suggests that they could be considered a form of academic language specific to these science classrooms. Brown and Ryoo (2008) explain the difference between vernacular and non-vernacular language, where vernacular language is used by particular communities (e.g., scientific terminology), while non-vernacular language is the language we use with friends or family that does not require a special knowledge base (usually considered 'everyday language'). Academic language, or the language of schooling, is often considered a vernacular language that is only used in the certain setting of school and within a specialized community. Since the students in these cases easily discuss and sensemake using their invented terms, it seems reasonable to say that in the setting of the classroom, the terms that students invented (pacmen, little men, etc.) were a vernacular language understood only by members of these classrooms. Being able to create vernacular terms also creates a shared sense of community, since students are creating representational tools in the form of language and models that only they understand.

Inventing terms also lends itself to creating ontologies and allowing for epistemic agency. Ontological innovation suggests that students develop theoretical constructs as a way of carving up the world to explain and participate in scientific discoveries (diSessa & Cobb, 2004). Students are able to engage in ontological innovation by inventing theoretical objects in their model. In Case 2, students create the theoretical objects of pacmen which evolve over the course of their model to become a type of ontology that students apply to a range of ideas. Pacmen originally were created to represent the idea of dye particles in the students' model, but with extension of their model, pacmen became a class or type of theoretical object. Pacmen transformed into any kind of theoretical object that would eat bbs, which made pacmen a type of ontology for the students' model. The language of pacmen plays a significant role in allowing students to develop these ontological innovations as students need the terms in order to define the properties and activities of these terms (e.g., puking pacmen and packaging pacmen). Allowing students to invent their own terminology also provides students with epistemic agency (Miller et al., 2018). Getting to choose, adapt, and refine theoretical objects and their activities provides a space for epistemic agency, and creates a unique opportunity for students to build knowledge from the ground up as a community. The students invented terms therefore are important for creating a space for tinkering and producing novel theoretical objects for model building.

Conclusion

In this study, I set out to investigate the intersection of modeling and tinkering in the science classroom. Specifically, I wanted to investigate if tinkering was possible with theoretical objects (ideas) and how 'idea tinkering' mirrored or differed from tinkering in engineering contexts. Using a multiple case study approach, I collected data from two semesters where university students, built models of light and color. Results showed that when provided with the opportunity, students are able to engage in tinkering activities with model and theoretical objects. These activities are iterative, playful, improvisation, and spur shifting goals to emergent problems. Furthermore, tinkering during novel model building requires an environment that allows for immediate feedback, open exploration, and fluid experimentation (Resnick & Rosenbaum, 2013). Tinkering provides a range of affordances including opportunities for epistemic agency (Miller et al., 2018), ontological innovation (diSessa & Cobb, 2004), and the pursuit of coherence mechanistic model (Hammer & van Zee, 2006). The activity of tinkering is something that is much more interdisciplinary and multidimensional than previously considered and should be taken into consideration as an essential activity needed in the science classroom. This being said, further research is still required and is outlined in greater detail in the next section.

Future Research

In this study, I proposed the activity of 'idea tinkering', and used evidence from classroom data to show how this activity is different from other activities seen in the science classroom; in that it is unique and is a kind of activity that should be set apart from other design or engineering practices as something that can sustain model building and sense making. The purpose of this study was to propose a kind of tinkering activity, 'idea tinkering', where students invent their own theoretical objects in pursuit of creating a novel mechanistic model of a complex scientific phenomena. The results from this study led to further questions and ideas for future research. First, I would like further investigation into what seems to initiate and sustain tinkering, especially in this unique way where students get to invent theories. Some students from this study seem particularly good at ‘idea tinkering’ while others are reluctant to engage, as it is not something that they have experienced before in the science classroom. From this perspective, it seems essential to explore how to get all students engaged in tinkering and how to sustain this engagement. It would also be interesting to examine what other aspects of engineering tinkering and engineering design could be critical in this theoretical tinkering. Common ideas around engineering tinkering and design include rapid prototyping, empathizing, ideating, and intentional and systematic testing. Further research could explore how these processes relate to and support tinkering with models and theoretical objects. Continued research would create a more holistic understanding of the role of tinkering in both model building and more generally in the science classroom.

In both cases of this study, students explored the topic of light and color, which is an abstract topic that sustains student curiosity and requires substantial sensemaking. The topic of light and color is unique in the fact that students usually have a superficial understanding of how color works, but a wide range of experience with color. Light and color are also abstract and only rarely covered in the science curriculum. This makes light and color an ideal topic to have students engage in for novel model building. For future research, it would be interesting to expand the tinkering repertoire and discover other abstract scientific topics that would also engage students in tinkering in the same way that the topic of light and color seems to. I suspect that topics such as time and energy may allow for tinkering like light and color, but further research would be needed to find out. Discovering more topics that sustain tinkering would make tinkering more accessible in the science classroom, and create more opportunities across science education for students to engage in tinkering during model building.

Lastly, language played a significant role in the development of theoretical objects and knowledge building of the class communities. In this study, students used ontological innovation (diSessa & Cobb, 2004) to develop a whole class of theoretical objects (pacmen) in their model that could be widely applied to a range of scientific phenomena (photosynthesis, global warming, color blindness, etc.). In developing these ontologies, students had to invent terms to describe these entities (little men and pacmen for example), and these terms became an essential part of the class vernacular. In turn, future research could examine the role of language within tinkering and model building. It could look at how invented terms become a kind of 'academic language' used by the class to develop their model. Future research could also investigate how the creation of terms is inherently, and authentically scientific, yet, rarely employed in the science classroom. Finally, investigating the role of invented terms could show how this playful terminology sustains tinkering and inspires the construction of novel mechanistic models.

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