ELEMENTARY STUDENTS' MULTIPLE REPRESENTATIONS OF THEIR IDEAS ABOUT AIR

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Abstract

This dissertation explores how students generate multiple external representations of their ideas about air, an "invisible" substance. External representations can serve a powerful role in placing students' ideas into the external world for reflection and abstraction. When provided the opportunity to represent their understandings of science in different ways, students generate increasingly coherent explanations of what they observe, including developing ideas about mechanisms that describe cause and effect. In this qualitative study, extended clinical interviews were conducted with twelve fifth-grade students from an urban public charter school. In study was designed to investigate students' ideas about air in the context of a linked-syringe device with the support of multiple representations. Students were given the opportunity to produce representations and to offer verbal explanations of the behavior of the syringes in a sequence of three interviews. In the first session, students were introduced to the linked-syringes, and they generated drawings to explain their thinking about air. In the second session, students created stop-motion animations of their explanations for air in the syringes. And in the final session, students built physical devices to demonstrate their ideas about air.

Careful analysis of each individual student's trajectory through the microgenetic design and a cross-student analysis reveal that the process of generating multiple representations facilitates how students think and reason about air. Drawings served to organize elements of the linked-syringe problem, providing students with focal points on which to direct their reasoning as they generated more precise explanations. Stop-motion animation supported students' efforts to make sense of processes that change over time, such as compressing the air inside the syringes. And, the construction of physical artifacts prompted students to think about air as a substance, as the activity allowed them to generate analogous physical models of the linked syringes. Furthermore, the students' productions provided the researcher with enhanced access to the substance of students' ideas as captured in their representations. The results of this study are presented in case-study form to highlight how representations serve as embodiments of the resources that students possess for making sense of science. This dissertation contributes to the resources perspective of the importance of external representations in students' development of coherent explanations of what they observe.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Motivation and Research Problem

The motivation for this dissertation grew out of my teaching. My first experience was in a ninth grade “engineering” course that I co-developed with a partner teacher. We capitalized on the nature of engineering design as a context for students to explore the major themes (e.g., force and motion) of a conceptual physics course. In one unit, students were given three small DC motors, three different fan blades, and the following prompt: which combination of motor and blade generates the most force? Students were excited by the challenge, but their first question was, “What do you mean by force?” The activity was intended as an opportunity for students to construct understandings of force; the task purposefully launched them into a process exploring the idea of force and how to measure it. Through a lengthy process of inquiry and design, students generated ways of measuring the amount of “push” each motor and fan blade combination produced. During this four-week project, I witnessed the power of providing students with opportunities to express their ideas in novel and unconventional ways. I came to realize that when students are engaged in creative problem-solving activities, much of their work centers on the use of everyday language, gesture, drawings, and explorations of physical materials - forms of representation whose use is not necessarily bound by fully explicit rules or grammars. Students drew sketches of contraptions involving levers and springs in attempts to generate ways to measure the force of each propeller. They created vivid analogies, argued about what constituted a force, and tinkered with physical materials to explore and develop their thinking. Through these diverse opportunities to express and work with their ideas, all of the students succeeded in measuring the varying amounts of “push.” Students shared their ideas through the drawings, physical constructions, gestures, and generative analogies that they produced. Through these varied forms, students demonstrated aspects of their thinking that were not apparent in their developing uses of scientific language, thinking that remained masked in their writing as well. Having alternative means to represent and explore their ideas successfully supported students’ efforts to think and reason. However, in the subsequent years that I have been in classrooms, I have recognized that the opportunities we provide for students to engage in various ways of representing their thinking have been too frequently limited. The remarkable array of ideas and understandings that my students displayed when given representational freedom begged the following question: are we limiting the abilities of our students to engage with complex ideas in science by restricting the ways in which they are able to express their thinking? This dissertation explores how students represent their understandings, and how multiple representations (both the process of production and reflecting on the representations produced) support students’ efforts to reason about and make sense of the natural world.

Research Context: The Importance of Multiple Representations

Previous studies in mathematics and science education research have been carried out in the area of multiple representations (e.g., Brizuela, 2004; Brizuela & Earnest, 2008; Goldin, 1998; Johnson, 1995; Lehrer & Schauble, 2000a, 2000b; Nemirovsky, 1994; Pozo & Gómez Crespo, 2005; Zhang, 1997; Zhang & Norman, 1994). The present study builds from these works while strongly emphasizing the role of *production* – student-generated, spontaneous, and often idiosyncratic expressions of ideas – across multiple external representational forms (see Pérez Echeverría & Scheuer, 2009). Students have been shown to produce insightful representations about science concepts through conventional systems of representation (e.g., written language, mathematical notation; see diSessa, Hammer, Sherin, & Kolpakowski, 1991; Elby, 2000; Lehrer & Schauble, 2000b, 2002; Sherin, 2000) as well as through less frequently used forms[1] such as stop-motion animations (Church, Gravel, & Rogers, 2007) and the construction of physical artifacts (Penner, Giles, Lehrer, & Schauble, 1997; Wendell, 2010). Conventional systems of representation are the socially constructed, widely utilized forms such as written language and mathematical notation. While these forms are used broadly in science classrooms, less conventional forms, such as stop-motion animations, are scarcely used in schools, thus possibly limiting students' opportunities to represent (and concurrently contemplate) complex and

[1] Also known as "hybrid systems," as they can include elements from conventional systems of representation (Martí & Pozo, 2000).

intricate understandings. Bamberger (1991) addressed this paradox when she noted:

> Students who are most successful, even virtuosos, at using their hands to build and fix complicated things in the everyday world around them are often the same students who are having the most difficulties learning in school. These students are frequently identified as having trouble in working with common symbolic expressions – numbers, graphs, music notation, written language – the "privileged languages" that form the core of schooling. With the emphasis in schooling on symbolic knowledge, it is not surprising that attention focuses on what these students *cannot* do, and it is also not surprising that the school world sees them not as virtuosos but as "failing to perform." (p. 38)

In school, success is often measured by students' mastery of conventional symbolic knowledge, but Bamberger alluded to the limitations of placing importance purely on the symbolic; many of students' powerful ideas and talents remain concealed by their abilities (or inabilities) to effectively manipulate conventional symbol systems to express their understandings. Conventional representations and symbolic knowledge are clearly important, and have been the focus of a number of studies on students' reasoning in science and mathematics (see Brizuela, 2004; diSessa, et al., 1991; Goldin, 1998; Goldin & Kaput, 1996; Goldin & Shteingold, 2001; Kaput, 1991). However, we must also recognize the potential of the unconventional and idiosyncratic representations that students generate for the development of reasoning skills, understandings, and their capacities for expressing their ideas in new ways. Moreover, externalizing ideas in *multiple* ways likely enhances both one's understanding of symbolic representations (both conventional and invented) and one's understandings of science (for examples in mathematics, see Brizuela & Earnest, 2008). In addition to the benefits for students, multiple representations also provide the educator (and researcher) with numerous perspectives on students' ideas and reasoning. Just as adults might use different representations to communicate ideas or improve their own understandings of phenomena, children's use of multiple representations provides a window into different aspects of their understandings and attempts to express their thinking. This dissertation study builds from the importance of representations in thinking and learning.

Research Questions

The goals of this study are to explore students' thinking about a common, yet quite complex, idea - air and a particle model of matter in the gaseous state.[2] More specifically, this research aims to investigate the relationships between students' ideas about scientific phenomena and external representations that they produce. The science topic chosen for this study is *air,* because it is an idea students are familiar with from a young age (Piaget, 1930/2001), and the unseen

[2] I choose the term "particle" in the present work to be synonymous with "particulate," as used by Nussbaum (1985). Additionally, the term "particle model of gases" is used because gases are the primary state of matter under consideration in the proposed study. Students may consider liquid and solid forms of matter; however, the study focuses on air and matter in the gaseous state.

nature of air makes it an interesting topic for representation research (see Chapter 2). Considering that air is a collection of gases, the role of the particle model of matter must also be considered, as this model describes the microscopic and macroscopic behavior of matter, including gases (see Wiser & Smith, 2008). Students in upper elementary grades often have experiences with the term *molecules* and possibly even *particles* (Brooks, Briggs, Driver, 1984; Nussbaum, 1985; Papageorgiou & Johnson, 2005). In representing something that is unseen, such as a gas, the use of a particle or discrete model can be quite productive for explaining certain phenomena (e.g., compression). Thus, as previously stated, while air is the topic on which this study will focus, ideas about the particle model of matter must be considered, as I hypothesize that a discrete model of matter assists students' attempts to make sense of gas dynamics (e.g., compression).

Combining the desire to investigate the impact of multiple representations on students' understandings with the richness of a topic such as *air* lead to the development of the following research questions, which guide the design and development of this study:

1. What ideas about air and a particle model of matter are students able to represent across different forms of external representation?
2. What are the relationships between students' productions in each of the representational forms and their understandings of air and the particle model?

3. How are students’ understandings of and reasoning about air and the particle nature of matter impacted by representing these concepts across multiple forms?
4. How is students’ reasoning about science influenced by the production and refinement of external representations?

Theoretical Perspectives on Reasoning and Representation in Science Learning

For this dissertation study, I take a constructivist perspective that assumes students construct a view of the natural world based on their interactions with objects in this world, their prior experiences, and a drive to understand what they see (Piaget & Inhelder, 1969). Furthermore, I adhere to the view that students’ words, gestures, and representations embody the conceptual resources used to generate and refine coherent explanations of their observations (Hammer, 2004; Hammer, Elby, Sherr, & Redish, 2005). In other words, Hammer et al. (2005) proposed a “manifold ontology of mind, of knowledge and reasoning abilities as comprised of many fine-grained resources that may be activated or not in any particular context” (p. 92). While I share this position, I offer an additional theoretical dimension to the “resources perspective” (Hammer, 2004; Hammer et al., 2005; Roseberry, Warren, Ballenger, Ogonowski, 2005; Warren, Ballenger, Ogonowski, Roseberry, Hudicourt-Barnes, 2001). Prior research and theoretical perspectives emphasizing the value of students’ conceptual resources tend to focus on students' ways of talking and reasoning verbally about the phenomena they encounter. Studies have demonstrated the generative power of students' intuitive ideas (Hammer, 1995, 2004) and everyday language (Roseberry et al., 2001). I conjecture that in addition to students' talking, the representations they spontaneously generate in various forms (e.g., drawings, animations, physical artifacts) are critical embodiments of their ideas and essential tools in their thinking and reasoning about science. This is not to say that other researchers adhering to the resources perspective have denied the role of representations in students' reasoning, however, representations (other than verbal utterances) have not traditionally been the explicit focus of these works. As such, I include students' representations (both the production of and interaction with) as critical aspects of how they express and refine their ideas; the representations that students produce are resources for transforming their cognition. Therefore, while I treat students' intuitive ideas as resources for constructing understanding in different situations, I offer the addition of external representations as embodiments of these resources. I contend that multiple representations can influence students' abilities to generate coherent explanations of that which they observe.

The ultimate goal of science education and science learning is for students to pursue coherent explanations that account for natural phenomena. For instance, as Russ, Scherr, Hammer, and Mikeska (2008) highlighted, "Progress in scientific inquiry is characterized in part by a shift toward reasoning about causal mechanisms" (p. 500). Mechanisms are defined as the linking processes between cause and effect, or as Schauble (1996) defined them, "The explanatory models, ... either structures or processes, that account for the observed phenomena" (p. 103). The explanations we want students to generate are those that include descriptions of some linking process. The level of detail, precision, and coherence of these processes are the metric against which we measure students' progress in scientific inquiry. Perkins and Grotzer (2005) highlighted the power of making causal patterns explicit for students' reasoning about complicated ideas in science, emphasizing the role these patterns serve in priming students to consider mechanisms. Similarly, Hammer (1995) described, "Students and physicists have rich stores of causal intuitions; reasoning about the causal structure of a situation can help them tap these resources" (p. 422). Tapping into ideas about causality allows students to begin generating more coherent explanations involving precise mechanisms; yet, reasoning about causality alone is not indicative of the same level of sophistication as reasoning about linking processes. In other words, as Russ et al. (2008) stated, "Causal reasoning ... serves as a starting point for the pursuit of underlying mechanistic explanations, but causal reasoning alone does not define mechanistic reasoning" (p. 506). Therefore, the goal is not simply explaining causality as much as it is the precise description of particular mechanisms. To achieve this goal, I argue that students *must* have opportunities to engage in an iterative[3] process of production and

[3] I choose the term "iterative" to reflect how students build on prior ideas and representations in a repeated fashion, even if the exact processes and representational forms vary.

interpretation of representations in order to reason about precise mechanisms. Prior research has indicated the importance of a focus on mechanisms, but has not gone far enough in recognizing the importance of student-generated external representations in the pursuit of coherent explanations. Thus, in this dissertation, I propose that constructing external representations of an unseen, like air, is an opportunity for students to engage in “reductionist” (White, 1993) reasoning that addresses the underlying mechanisms that explain their observations. In other words, students’ reasoning about causality and capturing, through external representations, the “entities that are not directly observable” (Chinn & Malhotra, 2002) is a focal point of this study.

The theoretical perspective on constructing meaning in science builds from the valuation of students’ ideas as resources and emphasizes capturing these ideas in external forms as means for students to specifically attend to causal patterns and mechanisms. Students’ intuitive resources are made partly explicit through this representational experience, setting them on a path of iterative production, reasoning, and refining of their explanations about air.

Overview of Dissertation Study

Given the complex, multifaceted landscape of resources and external representations used by students in their explorations of ideas in science, this study was designed to allow for multiple rich descriptions of students’ representational activities. The goal for this dissertation is to investigate what ideas students include in their representations, how those representations change and evolve, and the relationship between students' ideas and the multiple, iterated representations they produce. To achieve these ends, an extended clinical interview methodology (Duckworth, 1996) was employed with fifth-grade students from an urban school. All participants engaged in multiple interview sessions whereby they produced representations of their ideas about air in drawings, stop-motion animation, and the construction of physical artifacts.

I present the results of this study in three forms: (1) a case study of one student, (2) an analysis of multiple students' ideas about compression, and (3) a characterization of the variety of students' trajectories during the interview design. The case study features one particular student, Isis, and her ideas and representations from each of the three interviews; I report in great detail how her ideas and representations evolved and changed over the sequence of clinical interviews. The case study is intended to provide the reader with a thorough description of the study design and a sense of the experience each of the participants had in the interviews. The subsequent chapter presents results that compare all the participants' reasoning about and their representations of compressed air. And finally, the third chapter illustrates the uniqueness of each student's particular trajectory in this dissertation study. Students used similar ideas, reasoned about similar mechanisms, and represented air using similar symbols and inscriptions, but the individual trajectories that each student followed were unique and diverse. In sum, this dissertation presents results and discussion to critically analyze students' multiple representations of their ideas about air.

Chapter 2. Theoretical Framework & Literature Review

In this chapter, I present the theoretical framework for this dissertation study and a review of the literature on students' multiple representations and their ideas about air. The theoretical framework defines external representations in thinking and learning and presents the key theoretical positions that informed the design of this dissertation study. I also review the existing research about students' multiple representations in mathematics and science, and the literature concerning students' ideas about air and particles.

Representations in Learning and Doing Science

The process of developing and refining ideas in science is inextricably linked to the types of representations used to express and communicate these ideas. When scientists debate the intricacies of phenomena, they use graphs, mathematical expressions, drawings, diagrams, written language, spoken language, and even gestures to argue their points. Discourse in science relies on the frequent and varied use of representations as the instruments of discussion and argumentation. In other words, the *language* of science is multiple representations. Practicing scientists seamlessly translate among these multiple representations in attempts to communicate their findings (Chapman, 2000; García-Mila, Andersen, & Rojo, 2009; Latour, 1988; Ochs, Jacoby, & Gonzales, 1994). Different representations offer different affordances, and thus scientists use a multitude of forms to express, debate, and refine their ideas. At the core of these representations are scientists' efforts to explain observations through the continued abstraction of fundamental ideas (diSessa, 1983; Goethe, 1978), ultimately leading to the creation of explanatory models (Clement, 1993). Consider the evolution of a theory of gravity. Aristotle believed that heavy things fall faster; Galileo revised that model (by rather famously dropping balls from the Tower of Pisa); and Newton developed a mathematical relationship that elaborated on Galileo's model (Gribbin, 2002). Beginning with Aristotle's intuitive observations, the collective understanding of gravity evolved, over long periods of time, into what Newton eventually modeled using mathematical expressions. Stewart and Golubitsky (1992) described the scientific method as deeply dependent on mathematical descriptions that "capture essential fragments of how [scientists] think the world behaves" (p. 2). An essential element of the evolution of intuition (diSessa, 1983), as illustrated by the rough description of the evolution of the theory of gravitational force described above, is the invention, adoption, and appropriation of (idiosyncratic and conventional) external representations that capture these ways of explaining the world. Through multiple forms of representation, these ideas are shared, tested, refined, and can evolve into principles, models, and theories.

The importance of representations in the evolution of ideas from intuitions into laws is equally prominent for scientists as it is for students' efforts to make sense of the world. The lens for this dissertation is framed by scientists' dependence on multiple representations, while focusing on the ways elementary-aged students engage with, produce, and refine multiple representations in their reasoning about phenomena they encounter. Children develop the ability to represent reality at a young age (Piaget & Inhelder, 1966), beginning with idiosyncratic and individualized expressions that become the foundation of their eventual learning and appropriation of more conventional forms (e.g., oral language). Representations of understandings place ideas in the external world for reflection and abstraction (Kaput, 1991); they become part and parcel of cognition. In science, children's evolving intuitions develop concurrently with their capacity for producing representations; as children develop language, they develop means for explaining their observations. In other words, representations serve as tools that facilitate behavioral and intellectual transformations at both the individual and social level (Vygotsky, 1978). The integration of students' ideas with the construction of representations is featured in the context of students making sense of science; students concurrently develop their thinking as well as inscriptions for that thinking (Lehrer & Schauble, 2002). The following example frames this interdependence of representations and the ideas encapsulated in students' reasoning.

Consider a student drawing an explanation of how a parachute works. Contained within the drawing is a set of elements (e.g., letters, numbers, symbols) and ways of representing the relationships between these elements (Pérez Echeverría & Scheuer, 2009). The drawing contains a rich, interwoven collection of symbols, resources, and ideas that are uniquely combined to make sense of the parachute. In other words, the drawing does not contain a single fine-grained idea, but rather a combination of ideas embodied through symbols and inscriptions. For example, consider the fourth-grade

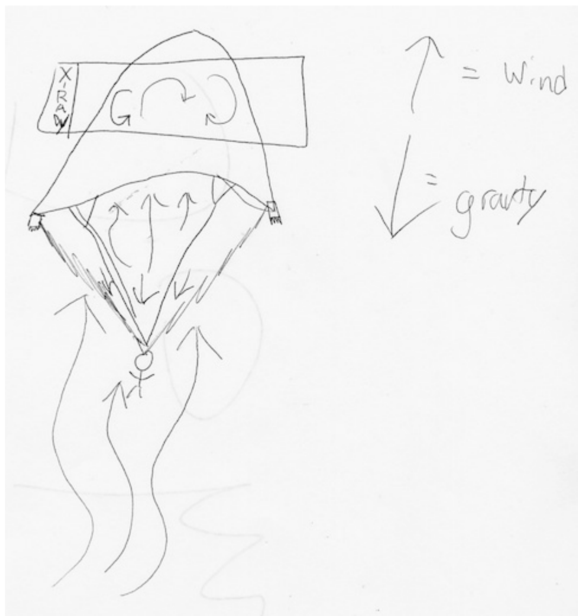

Figure 1. Example of a student's drawing of how a parachute works.

student's drawing of how a parachute works (see Figure 1). The drawing incorporates a multitude of ideas: wind, "gravity," air moving past the parachuter into the parachute, and a different type of air motion inside the parachute (as shown with the "X-Ray" in the drawing). These ideas are represented through arrows, written language, lines, depictions of the parachute, and a stick figure as the parachuter. At the production level (excluding particular utterances and gestures), this drawing illustrates how students' representations are composite structures of different ideas "activated" (Hammer, et al., 2005) through the construction of the drawing. The combination of ideas involved in producing the representation can be conceptualized as a momentary “model” - an artifact generated with the intent of explaining a particular phenomena - in much the same way that Clement (1993) wrote about explanatory models in science. In this student’s drawing, a number of ideas are combined to create a momentary model that describes how a parachute works. This student included ideas about gravity pulling the parachuter downward (likely a school idea, possibly supported by experiences dropping things), of air resistance (denoted by the word “wind” and the upward facing arrow), and perhaps more intuitive ideas about the air inside the parachute using an “X-Ray” window and circular arrows. This student produced a drawing that placed his intuitive explanation (which likely blends everyday and school ideas) into a world where he could reason and reflect on the quality of these ideas. Thus, external representations created by the student allow for the embodiment of intuitive ideas and resources in the construction of explanations for what he or she observes.

Making “Unseens” Visible

The particular content topic for this study, air as a material substance, was chosen for a multitude of reasons. Nearly eight decades ago, Piaget (1930/2001) investigated children’s reasoning about mechanisms, and he reported studies involving young children’s conceptions of air and wind. He found that young children often associate the presence of air with observations of air currents causing objects to move, such as wind moving the leaves on trees. From this point of view, Piaget claimed that students must observe some effect in order to acknowledge the presence of air. Students as young as five years old are familiar with the term "air" (Driver, Squires, Rushworth, & Wood-Robinson, 1994); thus, one can argue that students have encountered the idea, and likely thought about it, from a very young age. While air is used in everyday conversations with great frequency, and it regularly causes observable events (such as blowing doors closed or moving leaves on trees), it remains "unseen." An invisible causal agent, like air, requires students to create explanations based on their observations and prior experiences. Students must generate ways of explaining the effects caused by air, such as wind blowing leaves on a tree or doors closing because of shifts in air pressure in the room of a house; students use intuitive ideas to begin the process of constructing explanations (Hammer, 1995). Thus, air as an "unseen" is a suitable target for studying student reasoning about "entities that are not directly observable" (Chinn & Malhotra, 2002, p. 186). As a platform for studying representation, unseen agents create a unique opportunity for exploring how students invent external representations for the processes underlying their observations. For example, in order to explain how a shift in air pressure in a room can cause a door to close, a student must explicitly describe the process he or she believes was responsible for the event. In doing so, oral language may not be the most appropriate medium through which to provide these descriptions. Other researchers have studied students' reasoning about mechanisms (see Russ et al., 2005), however these studies have primarily focused on students' utterances and verbalizations. Generating other, non-verbal external representations of unseen agents provides the researcher with a unique window not only into how students make sense of ideas in science, but also how they learn to capture these ideas externally. Thus, the unseen nature of air makes it a compelling topic for investigating relationships between students' ideas and the external representations they produce. Furthermore, given that air is a mixture of gases, within students' reasoning about air exists the potential for ideas about the particle model of matter to surface. Thus, while air is the focus of this study, students' ideas about particles and the use of molecules or "parts" of air to describe specific phenomena are encompassed by the topic. Within the context of air, this dissertation considers the fundamental role that multiple external representations play in students' thinking and reasoning about mechanisms to explain their observations.

Defining Representation

The centrality of representation in thought

Piaget (1936/1977) presented a powerful story about his daughter Lucienne and the fundamental importance of representation. Young Lucienne (age 16 months) is presented with a cardboard matchbox containing a watch chain. The lid to the matchbox is open as widely as it can be, and the chain, clearly visible, is coiled inside the box (where Lucienne has placed it in an earlier episode). She takes the box and immediately inverts it, allowing the chain to fall out; Lucienne used a familiar action (i.e., inverting the box) to find success in a new situation. She is then presented with the same box containing the chain, only the opening has been reduced to 3 millimeters, a gap smaller than her finger, so she may not use her finger to remove the chain. Lucienne attempts to grasp the chain, but fails repeatedly. According to Piaget, at this point she "only possesses the two schemata: turning the box over in order to empty it of its contents, and sliding her finger into the slit to make the chain come out" (Piaget, 1936/1977, p. 238). Lucienne then produces the most delightful gesture: "she looks at the slit with great attention; then, several times in succession, she opens and shuts her mouth, at first slightly, then wider and wider!" (Piaget, 1936/1977, p. 238). Lucienne uses her own body to represent the future action she wished to achieve; the opening and closing of her mouth are a kinesthetic representation of an action that she performed with her hands only moments later, successfully retrieving the chain from the box. Moving her mouth was a kinesthetic representation that aided Lucienne in solving the problem she confronted. Piaget uses this story to describe the genesis and importance of *representation* for the child.

Lucienne's engagement with the matchbox brings to light the importance of representation in *facilitating* actions and thoughts for students and adults of all ages. Before she had achieved the ability to represent the action of opening the box with her mouth, Lucienne had failed in attempts to retrieve the chain. As Nelson (2009) remarked, "Representation is not the 'natural' first mode of thinking and does not occur in infancy" (p. 3). However, the advent of representation provided Lucienne with this opportunity to think about the action she wished to achieve prior to physically performing it. Lucienne's externalization of an idea helped her to develop a scheme for retrieving the chain from the box; her representation enhanced her efforts to achieve her goals.

What is representation?

Representation is a somewhat ubiquitous term in many fields of social science research, with a variety of definitions and uses. Kaput (1985) suggested that representations are "undefined primitive(s) whose meaning unfolds gradually through usage within a particular domain of inquiry" (p. 38). In the English language, the term "representation" is used in a number of different ways, making it a difficult word to define. The literature suggests a diversity of definitions for representation: Enyedy (2005) offered that representation is "the act of highlighting aspects of our experience and communicating them to others and ourselves" (p. 427); Goldin and Shteingold (2001) suggested that a representation is "typically a sign or a configuration of signs, characters, or objects...the important thing is that it can stand for (symbolize, depict, encode, or represent) something other than itself" (p. 3); and Lee and Karmiloff-Smith (1996b) affirmed that representation establishes a "stand for" relationship between referent and sign (see also Kaput, 1991, 1998). Representations are often considered from two perspectives, internal and external (Goldin, 1998; Zhang & Norman, 1994).

However, this distinction may be spurious (Nemirovsky, 2009), as discussed below. Thus, I will first consider representation in a broader sense, as constituting some measure of "stand for" or "refer to" relationship.

The "stand-for" relationship

Much of the early work on representation stems from linguistics and attempts to unpack the complex relationships between sign, signified, and signifier (de Saussure, 1959; see also Barthes, 1968). At the most basic level, representation has been treated as a "stand for" (DeLoache, 1996; Goldin & Shteingold, 2001; Kaput, 1998; Lee & Karmiloff-Smith, 1996b; von Glasersfeld, 1987) or "corresponding to" (Kaput, 1998) relationship between one part of an individual's experience and another. For the purposes of the present argument, I group "stand for" and "corresponds to" together, as done by Kaput. However, it is noted that upon more careful analysis of how representations are generated, these phrases can be considered different ways of viewing representational relationships. Stand-for relationships typically consist of two entities that can be interchanged to represent the same referent – for example, the use of acronyms like "scuba" to *stand for* "self-contained underwater breathing apparatus." There is a presumed one-to-one relationship with "stand fors" that is evident by the replacement capability. In other words, the representation is equivalent to the referent, or the signifier is transposable with the signified. However, "corresponds to" relationships do not necessarily imply or require the same interchangeability.

These relationships tend to be more analogous in nature, or they tend to point to specific aspects of the referent – for example, children's spontaneous use of analogies in describing scientific phenomena. There is a sense of "wholeness" to a stand-for relationship that is not required with corresponds-to relationships. Students producing external representations may generate stand-for relationships or corresponds-to relationships, depending on the context and their intent. I choose to use the term "stand for" more generally in this dissertation (see Goldin & Schteingold, 2001), however, the existence of potential differences between the representational relationships each term implies is duly noted.

While there is some general agreement that representations establish "stand for" relationships (Kaput, 1998), the spoken, written, drawn, and even gestured entities can carry different meanings. An adult, presumably operating with a sufficient knowledge of a conventional system of representation (such as written language), continually varies the meaning of representations depending on context and situation (von Glasersfeld, 1987). While there are conventional representations, there are not always conventional meanings. Therefore, in defining representation with regard to students, it is important to consider representation as a useful referential-communicative tool (Tolchinsky-Landsmann & Karmiloff-Smith, 1992). Students learn the communicative aspects of representation from early ages, and this dimension influences how they go about constructing representations of their ideas. A further distinction that defines representations in the context of this dissertation is that between the internal or mental representations and the external representations, that is, those having some perceivable presence in the world.

Internal vs. external representations

Literature reporting traditional approaches to cognitive research has focused upon representations that exist exclusively in "the mind" (Zhang & Norman, 1994). These *internal representations* are the subject of a large body of literature on knowledge organization in the mind, also referred to as students' internal conceptualizations (Lesh, Post, & Behr, 1987) or mental representations (Brizuela & Earnest, 2008). Donald (1991) suggests that as cultures have developed, they have relied more on external memory media, devices such as language and written notation systems that offload cognition onto the external world, subsequently freeing working memory for use in more complex tasks. Other researchers have supported Donald by focusing on external representations (i.e., those displayed on bi-dimensional spaces, such as writing, numerical notation, and drawing, and those that are not, such as gesture or spoken language; Even, 1998; Martí & Pozo, 2000), and arguing for the primacy of putting ideas in the external world in the development of cognition and thought (Olson, 1994). Goldin (1998) defined *external representations* as "the shared, somewhat standardized representational systems developed through human social processes" (p. 146) supporting the idea that cultural evolution plays a critical role in the development of these systems. Goldin and Kaput (1996) stated, "The distinction that we make between external and internal systems of representation is itself simply a constructed model, developed by an observer or community of theorists to help explain an individual's observed behavior, or the behavior of a population of individuals" (p. 407). Defining these concepts independently is consistent with classification schemes for the purposes of research; therefore, I am not critical of Goldin (1998), Goldin and Kaput (1996), or Martí and Pozo (2000).

At the same time, one must acknowledge the relationship between internal and external forms of representation in order to avoid false implications of duality. This "phantom of dualism" (Pérez Echeverría & Scheuer, 2009) that the internal/external distinction evokes fuels the debate over whether there can exist such a separation. Pérez Echeverría and Scheuer (2009), for instance, raised the question: by focusing on external representations, "are we establishing an absolute frontier between outer and inner worlds?" (p. 7). They warned against considering mental representations to be simply a collection of reproduced images, written notations, colors, sounds, or even gestures. To imagine that a child sees an image and generates a carbon copy of that image in the mind ignores the complexity of the relationship between the external and internal. Discussions whereby this literal mapping scheme is evoked have a tendency to emphasize the "phantom of dualism" because they downplay the role of sensory experiences in perceiving information, which some researchers have warned is a dangerous trend in representations research (Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009). The act of externalizing understanding involves a continual remapping of that conceptual object to the understanding one has. Such a process of remapping is exactly what Nemirovsky (2009) described: students do not copy what they perceive onto their mind; rather, they reconstruct connections between perception and understanding. Vygotsky (1978) emphasized that cultural symbol systems (e.g., language) provide learners with access to ways of thinking about the natural world; but, he also took great care to discuss the "internalization" processes that provide for this sort of mapping between idea and representation. Thus, when the focus is placed on internal versus external representations, the constant interplay between understanding and externalizations is essentially ignored. As some researchers suggested (Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009), the focus needs to be placed on the inscriptions, notations, and symbolic expressions that students produce in particular learning environments.

I must briefly comment on the diversity of opinions regarding terminology around external representations. While some researchers and theorists intentionally avoid the term *symbol* (Lee & Karmiloff-Smith, 1996b), others actually prefer to use the term *symbol* (Gardner & Wolf, 1983; Nemirovsky, 1994). As mentioned above, mathematics education researchers have primarily used the terms *notation*, *inscription,* and *symbol*; however, these classifications fail to include gesture as a legitimate form of external representation, which some researchers believe are just as important as those representations existing on paper (Goldin-Meadow, 2003; Noble, 2003). I acknowledge these terms and additionally recognize gesture as a legitimate form of representation.

Furthermore, regardless of the particular terms - symbol, notation, inscription - it is critical to remember that representations in these forms do not constitute direct windows into student's internal representations. Rather, a possible alternative could be to refer to students' external representations as "externalized representations" (Scheuer, personal communication, March 4, 2009), which acknowledges the role of the ideas and thoughts the child holds that may not be accessible through the representations they produce in particular contexts. An externalized representation is whatever observable artifact, gesture, or verbalization the child may make which is inextricably linked with whatever form of mental representation one envisions. However, I retain the term external representation herein to remain consistent with the literature.

The present work is primarily concerned with externally produced expressions that have a physical presence and that are typically referred to as notations or inscriptions in mathematics education (Brizuela & Earnest, 2008; Goldin & Shteingold, 2001; Lee & Karmiloff-Smith, 1996b; Lehrer & Schauble, 2002). In this dissertation, I refer to students' representations on paper and in animated form as *inscriptions* containing *symbols*. The physical artifacts constructed by students are considered *representations*, and all three forms fall under the category of *student productions*. In addition to these productions, I characterize students' use of particular *symbols* as elements within their productions intended to denote a particular aspect of the problem or idea, such as a *dot* serving a symbol for *air*. It is important to remember that even though in this dissertation I may focus on students' externally-produced representations, I certainly acknowledge the lurking presence of "the phantom of duality"; my focus on the external assumes that those ideas captured in representations are part and parcel of whatever structures exist internally.

Systems of representation

Some external representations and modes of expression can be organized into systems of representation (Gardner & Wolf, 1983; Goldin & Shteingold, 2001; Nemirovsky, 1994). Modes of expression that are used as conventional referential-communicative tools and form systems must meet two central conditions: they must have elements (e.g., signs/symbols, inscriptions, notations), and they must have rules that govern how elements are combined; in conventional systems, both the elements and the rules are socially constructed and widely agreed upon. A single notation or inscription is simply a signifier with minimal meaning unless it is situated within a larger *system of representation* (Gardner & Wolf, 1983; Goldin, 1998; Goldin & Shteingold, 2001). Nemirovsky (1994) differentiates "symbol use" from "symbol systems" by maintaining that systems involve rules. When students learn representations, they must learn not only the notations and inscriptions for elements within the system (e.g., letters and digits), but eventually the rules of the system as well. However, not all systems have formal, universally accepted rules. For example, classifying drawing as a system of representation is debatable because the particular elements and rules for combining elements are difficult to explicitly define. Drawings can include elements from written language (see Figure 1) and numerical elements while still communicating meaning, which creates a problem when trying to define specific elements and rules within the system. Lehrer and Schauble (2000a) used the term "representational model" to refer to such representations that can be part of a system but can also be unconventional and unsystematic (Brizuela, 2004). The important overarching idea to remember when discussing systems of representation is that each system contains elements and rules, and students must learn both aspects en route to becoming proficient within each system.

Brizuela (1997) showed that failure to adhere to the rules of a system does not necessarily detract from the meaning of the representation for the child. Students are indeed aware of systems of representation as well as the symbols that comprise those systems; however, conceptual dilemmas arise as they attempt to represent ideas that they are still shaping. Additionally, students may experiment with uses of arrows, numbers, and combinations of conventional elements in unconventional ways (Brizuela, 1997) in their attempts to find meaning in the uses of the elements, and to convey meaning using the elements. The use of conventional elements in invented manners can help students understand not only the concepts but also why specific representations are useful in reference to certain ideas (diSessa *et al.*, 1991; Enyedy, 2005). Thus, while students are aware of the various symbols and features of different systems of representation, their invented use of these elements is one way through which they can find meaning.

Given the debate amongst researchers as to the specific requirements a representational form must meet to be considered a system, I choose to avoid calling the representations included in the dissertation systems and refer to them as types or forms instead. However, the theoretical perspective that students must come to understand both elements and how those elements can be combined to convey meaning is fundamental to how students represent their own ideas, either in conventional or idiosyncratic ways. This process of exploring the forms (or systems) serves to promote thinking and reasoning and is at the cornerstone of why I share with others the perspective that representations are thought amplifiers.

Representations as thought amplifiers

Understandings objectified through representations are accessible for reflection and abstraction (Kaput, 1991), making the external artifact a means for amplifying thought. In other words, representations can facilitate thinking about complex ideas (Roth & McGinn, 1998). When combined with other representations, scientists and children alike are afforded an opportunity to reflect on a number of ideas simultaneously. Thus, the representation serves as a vehicle for heightening conceptual complexity, while providing a level of organization and structure that may be more difficult to achieve internally. Ideas captured in representations become “objectified” (Olson, 1994), and that quality of external representations can enhance metacognitive activity (Flavell, 1987). As Pérez

Echeverría and Scheuer (2009) summarized, representations enhance, "metacognitive skills to revise products as well as to tune and monitor production procedures, in order to accomplish higher semantic and syntactic standards and pragmatic efficiency" (p. 5). Therefore, the external forms serve to elevate one's awareness of and productivity with representing understanding, while also promoting the continual refinement of one's thinking.

More broadly, external representations have also been found to influence entire domains of knowledge, such as with the introduction of the Feynman Diagram to the field of theoretical physics (see Kaiser, 2005; Schweber, 1986). Richard Feynman's proposal of this new representation shaped the thinking of quantum dynamics researchers, and his diagrams became a new way of approaching the concepts of the domain. In this case, the representation served as a thought amplifier to the extent that it influenced fundamental concepts in physics. However, Feynman's diagrams were not initially adopted, rather a gradual process of introducing these diagrams and negotiating their meaning to optimize their purpose led to their eventual acceptance. In this sense, the particular representations become amplifying tools (Lévi-Strauss, 1963)[4] that transform ways of thinking and possibly the structure of knowledge itself (Olson, 1994). The sequence of production, adoption, and optimization is similar to students' attempts to represent new ideas in mathematics and science. Students, too, iteratively produce and refine representations in attempts to make them

[4] See also the idea of "cultural amplifiers" (Cole & Bruner, 1971; Cole & Griffin, 1980)

meaningful, a process which has been termed “progressive symbolization” by some researchers (Enyedy, 2005; Lehrer & Schauble, 2002). The power of external representations in amplifying thought is rooted in the invention of new ways of capturing and communicating ideas. Students producing representations is a primary component of this dissertation, and the particular importance of inventions deserves further consideration.

Students as inventors of representations

When a student writes or draws something, that externalization, we assume, is linked to an understanding. In other words, the signified is linked to the signifier by some “associative bond” (de Saussure, 1959, p. 66). However, once a representation becomes objectified (e.g., in a written form on paper or an intentional gesture), the link between the conceptual object and the understanding needs to be re-constructed. Such is the case for students adopting conventional systems of representation such as written language or mathematical notation; for example, what a negative sign represents in reference to velocity and motion (Nemirovsky, 1994). Students must construct a link among the conventional notations such as letters and numbers, but they must also continually re-construct the association between whatever idiosyncratic representation they produce and their own ideas (Goldin & Kaput, 1996; Lehrer & Schauble, 2002). There is a process of production and realignment that deeply impacts how students represent their ideas, and this process is rooted in students' natural competency to invent representations.

diSessa, et al. (1991) illustrated this natural competency for inventing representations in their work on "inventing graphing" with 6th-grade students. Their study revealed that students have a powerful ability to invent representations with particular purpose (e.g., showing motion), but that they also have a powerful ability to critique representations (Azevedo, 2000; Danish & Enyedy, 2006; diSessa et al., 1991; diSessa & Sherin, 2000). Such evaluations of representations (either the students' productions or representations with which they are presented) are central to the reconstruction of the link between the object and the signified. The theory of "Meta-representational Competence" (MRC, expanded in diSessa, 2004; diSessa & Sherin, 2000) encompasses students' native[5] competence for inventing representations (diSessa et al., 1991; Sherin, 2000) and native ability to critique representations (Azevedo, 2000). Inventing and critiquing have been the focal points of MRC research (with further dimensions beginning to emerge in diSessa, 2004), and they deserve adequate attention when considering students' representations. Bamberger (2006) proposed that for musicians and students learning music, "performances (both silent and out-loud) involve a process of active, sense-making occurring in real-time" (p. 70). While Bamberger's work refers to music, I believe it is pertinent to the current discussion. Consider the externalization of understanding to be a

[5] diSessa (2004) takes care to note that the term "native" does not imply genetically determined ability, but rather competence is "gradually developed through cultural practices in and out of school" (p. 294).

performance, whereby the student is demonstrating some aspect of his or her thinking. The practice of real-time sense-making accurately describes how the student produces and reflects upon a representation, as to continually rebuild the link between the production and the embodied idea. A second attempt to reproduce the same representation will likely reflect this newly formulated association and may result in a more complex or refined representation. Such a process of production and re-representation is captured by the idea of "progressive symbolization" (Enyedy, 2005; Lehrer & Schauble, 2002). Progressive symbolization helps to explain how "the process of progressively refining one's representation of some aspect of the world can contribute to a deeper understanding of a domain" (Enyedy, 2005, p. 428). In the present study, building from these theoretical underpinnings, students were afforded the opportunity to produce and progressively refine their representations of air in multiple representational forms. It is interesting to consider the word "invention" when thinking about the representations students generate. While the idiosyncratic forms that students construct could be considered invented uses of symbols, notations, or inscriptions, often the representations student create in drawn forms (or others) contain elements borrowed from other contexts. For example, a student using lines to show the movement of air did not invent lines, but rather created a context within which to use lines to show air. Thus, perhaps "production" is a more appropriate term to describe a student's process of constructing a representation. In that sense, a goal for this study was to explore the externalization (or production) and re-linking process in refining physical representations as well as verbal explanations of air. Thus, I review the literature on students' ideas about air, particles, and multiple representations to complete the framework from which this dissertation study was designed.

Literature Review on Multiple Representations and Students' Ideas About Air, and Particles

This dissertation explores the production and refinement of multiple external representations of air as processes through which students develop explanations of their observations. Thus, it is important to survey the literature on multiple representations and students' ideas about air, not only to inform the design of this dissertation study, but also to situate the results and conclusions of this study within the overall framework of how students' reasoning and their external representations are considered in education. As such, I review the literature on students' ideas about air and particles and the research involving multiple representations in mathematics and science. Finally, I present the results of a pilot study in which I explored the relationships among ideas, reasoning, and representations of air as a first step towards the design of the main dissertation study.

Students' conceptions of air

A scientifically accepted explanation of air as a substance considers air as a collection of gases described by the particle model of matter (detailed description provided below). Alternatively, a more precise model for the behavior of substances in the gaseous state, like air, is the Kinetic-Molecular Theory of Gases (Halliday, Resnick, & Walker, 2005). This theory suggests that particles in gases are widely spread (relative to liquids and solids), and they constantly collide with the walls of a container and with other particles. Attraction and repulsion forces in gases are considered to be negligible, as collisions are what dictate much of the observed behavior of gases, such as pressure or temperature. Still another approach to modeling and explaining air and pressure is from a fluid dimension, where air is conceived of as a fluid quantity (e.g., the Navier Stokes equations). Ultimately, there are many ways of conceptualizing, modeling, and explaining air, and students' ideas about air, air pressure, and the particulate nature of matter are well documented in the literature (Besson, 2004; Brook et al., 1984; deBerg, 1995; Driver et al., 1994; Johnson, 1995, 1998a, 1998b, 1998c; Lee, Eichinger, Anderson, Berkheimer & Blakeslee, 1993; Nakhleh, Samarapungavan, & Saglam, 2005; Novick & Nussbaum, 1978, 1981; Nussbaum, 1985; Papageorgiou & Johnson, 2005; Piaget, 1930/2001; Pozo & Gómez Crespo, 2005; Pozo & Lorenzo, 2009; Séré, 1982, 1985, 1986; Tytler, 1998). Many studies investigate students' thinking in regards to matter in the gaseous state, but air is a term and a concept that students encounter in many different contexts from a very young age;

air deserves special attention, separate from conceptions of gas as a state of matter. Thus, both the literature on air and the literature on the particle model for gases inform the present work, and are reviewed accordingly.

As previously mentioned, Piaget (1930/2001) was one of the first to study young children's ideas about air, wind, and pressure. In studies focusing on causality, he found that children strongly associate the presence of air with movement; that is, air only exists when there is a perceivable motion of air, like wind. One task Piaget (1930/2001) used to explore children's thinking was to have participants clasp two hands together to generate pressure between the palms that yielded a small current of air; children of different ages (and stages) explain the effect in different ways. Younger students tend to believe that air only exists outside in nature and not in a room such as where the interviews took place; the air streaming out of their hands in the example task came from some other source (for some students, the hand generated the air). Older students, however, eventually realize that there is air inside the room, and that the hands simply create a small stream of air movement using the air already existing in the environment. Similarly, younger students tend to think that trees generate wind, while older students recognize the role of air currents in moving the leaves on trees. Piaget's (1930/2001) work paved the way for other researchers to examine students' causal reasoning, specifically the relationship between observed movements and the presence of air.

Séré (1982, 1986) conducted classroom sessions and clinical interviews with students ages 11-13, and was able to confirm many of Piaget's findings concerning associations between air and movements. Séré (1982, 1986) reported that by age 11, students generally accept the idea of air in open containers, speaking about air moving (i.e., wind) into a jar through the opening, for example. Many students continue to only associate the existence of air with the presence of some movement (as Piaget found), such as with wind; a result confirmed with younger students (ages 6-8) by Borghi, De Ambrosis, Massara, Grossi, and Zoppi (1988) as well. Séré (1982) also found that only a small percentage of 11-year old students identify air in static conditions (such as in closed containers), but by age 14 the majority of students are aware of air in static conditions (see also Driver et al., 1994; Tytler, 1998).

Focusing less specifically on the associations between air and movements, Borghi et al. (1988) found that students ages 6-8 openly discuss air, and they tend to focus on pre-causal explanations (descriptions of observations) and references to the function of air in aspects of life. Séré (1982, 1986) found students ages 11-13 are comfortable discussing air as well, with some acknowledging the existence of an atmosphere (Driver et al., 1994), and many students admitting that air takes up space and its volume can be changed (deBerg, 1995; Driver et al., 1994; Tytler, 1998). With regards to the ability of air to transmit forces, nearly all students admitted that air "pushes against things," and some students specify the direction of force, claiming that air can push things forward (Driver et al., 1994).

Despite many burgeoning ideas about air, by age 16 less than one-quarter of students consider air as having weight (Driver et al., 1994), which suggests they are familiar with the effects of air, but less comfortable explaining the composition of air as a substance. These findings are completely plausible when one considers that students make sense of the natural world using their prior experiences and conceptual resources; they have seen the wind move leaves on a tree, air move objects on the ground, and they have experienced aspects of air in life, such as when breathing. However, these experiences and observations do not require one to contemplate the material composition of this "unseen" material that students learn is called "air" at an early age. The science of air as a mixture of gases explained by the particle nature of matter is considerably more complicated; the students' task, thus, becomes reconciling scientific ideas such as the particle model with their everyday experiences with air and wind.

Students' conceptions of the particle nature of matter in the gaseous state

Physicists' attempts to explain the physical world over centuries of investigation have developed a description of matter as consisting of small particles in constant, random motion. Richard Feynman (Feynman, Leighton, & Sands, 1963) emphasized the centrality of this notion:

> If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on the next generations of creatures, what

> statement would contain the most information in the fewest words? I believe it is the *atomic hypothesis* (or the atomic fact, or whatever you wish to call it) that *all things are made of atoms - little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another*. In that one sentence, you will see, there is an *enormous* amount of information about the world, if just a little imagination and thinking are applied. (p. 1-2)

Feynman positioned the "atomic hypothesis" as the cornerstone of scientific knowledge, and he alludes to the generative power of this relatively simplistic idea for making sense of the natural world; students' introduction to and adoption of this model in their thinking and reasoning is a primary concern in science education.

Fensham (1994) argued that the widespread failure of students to accurately conceptualize the particulate model of matter suggests that the teaching of this model should be delayed until high school, at the earliest. I strongly reject this argument, and the literature supports the position that students are capable of understanding aspects of a particle model at elementary and middle school ages; moreover, students can reason in complex ways about particles and molecular motion. While a great deal of the literature reports students' understandings of the particle model as "alternative" ideas from what modern science purports (Brook, Briggs, & Driver, 1984; Novick & Nussbaum, 1978, 1981), a resources perspective supports the argument that elements of students' thinking about particles can be useful in their eventual construction of normative ideas (see Johnson, 1998a). For example, Brook et al. (1984) found that more than 50% of high school students use particle ideas without necessarily comprehending other essential elements of the model. Students tend to incorporate particle representations with greater frequency (Driver et al., 1994; Nakleh & Samarapungavan, 1999) and consistency (Pozo & Gómez Crespo, 2005) when referencing matter in the gaseous state as opposed to matter in liquid or solid forms. Thus, a focus on air and gases may tap into students' reasoning abilities with regard to particle and molecule ideas, especially as students engage in expressing their ideas across multiple forms of representation.

Research on multiple representations

According to Pérez Echeverría and Scheuer (2009), "The use of alternative external representations to describe a single situation assists the explication of epistemic attitude, across developmental periods, learning situations and domains of knowledge" (p. 11). Other researchers have made a similar argument, where attempts to express ideas across systems of representation are shown to be beneficial for developing understanding (Brizuela & Earnest, 2008; Lehrer & Schauble, 2002). One specific reason for the benefit of using and producing multiple representations lies in the possibility that each system of representation may highlight aspects of a problem that others do not (Kaput, 1998; Pérez

Echeverría & Scheuer, 2009; Zhang & Norman, 1994). That particular conceptual features are made more salient in certain systems, and that specific types of reasoning are supported by specific types of representations, are both stances that are supported by the literature in both mathematics and science education.

A distinction is necessary prior to the review of the literature on this topic. External representations are considered in this section in two different manners: *expressively* as well as *interpretively* (Toth, 2000), or perhaps more classically as both *productions* and *comprehension* (Eskritt & Lee, 2007; Lee & Karmiloff-Smith, 1996a). An expressive representation or production is generated by an individual in an attempt to convey information to oneself or to a broader audience. These externalizations can be idiosyncratic, conventional, or a combination of both. Alternatively, specific representations are presented to students for their interpretation and comprehension, such as with many computer software applications and graph interpretation tasks (Nemirovsky, 1994). Regardless of the particular type of externalization, the general tenets of how students learn to use and appropriate these representations hold relatively consistent. Therefore, studies involving both production and comprehension will be included in this review.

The research in science and mathematics education has provided evidence that students can develop richer conceptual understandings and deeper knowledge of representational practices when the educational activities involve the use of multiple representations. Specifically, the variety of perspectives inherent in the many forms of representation provide for variance regarding which aspects of the problem are made apparent; highlighting a variety of conceptual aspects through multiple representations fosters deeper insight for students (Brizuela & Earnest, 2008; Kaput, 1998). Highlighting different conceptual elements of the same problem can support students' identification of patterns across representations. Complex language and circumstantial issues can also be unpacked by clarifying aspects of the problem through different modes of expression (Schwartz & Yerushalmy, 1995). The use of multiple representations to increase insight has been shown to specifically help students grasp concepts like mathematical similarity (Lehrer, Strom, & Confrey, 2002), graphical notations of algebraic concepts (Schwartz & Yerushalmy, 1995), how to model plant growth (Lehrer & Schauble, 2002), and position versus time graphs (Nemirovsky, Tierney, & Wright, 1998; Thornton, 1987). As Bamberger (1991) suggested, for many individuals (students and teachers), unpacking the problem involves the exploration of many forms of that problem; similarly, Brizuela and Earnest (2008) argued that, "Different kinds of conceptualizations…can be explored by navigating across different representations of the same problem" (p. 299).

Zhang and Norman (1994) introduced the concept of *representational effect* to address this issue of different representations linked to the same conceptual aspects. They define the effect by saying, "Different isomorphic representations of a common formal structure can cause dramatically different cognitive behaviors" (Zhang & Norman, 1994, p. 88; see also Kaput, 1998). In studies investigating well-known problems like tic-tac-toe (Zhang, 1997) and the

Towers of Hanoi (Zhang & Norman, 1994), they were able to show that individuals showed varying ability to solve the problem based on the representation presented. Parnafes and diSessa (2004) found similar results when investigating middle school students' understandings of motion in two different representations. Their findings suggested a difference in reasoning styles based on the type of representation on which the students focused. In these examples, the students were tasked with comprehending computer-based representations (Parnafes & diSessa, 2004; Zhang, 1997; Zhang & Norman, 1994). These studies have shown that interpreting and comprehending representations across multiple systems can impact students' reasoning in mathematics and science. However, this dissertation study emphasizes students *generating* representations in multiple forms; instances of students *producing* representations are also powerful contexts for exploring thinking and reasoning (Toth, 2000).[6]

Brizuela and Earnest (2008) reported on elementary school students learning algebraic concepts. The students were presented with a problem and asked to first verbally articulate their view of the problem, then put on paper some representation of the problem, then generate tables, and finally discuss graphical representations. The researchers found that as the students progressively represented the problem, "the explicit and implicit qualities of notations continually refined and enhanced their understandings of the problem" (Brizuela & Earnest, 2008, p. 282). Brenner et al. (1997) showed similar results in algebra,

[6] It is important to note that educational activities do not have to be exclusively interpretive or expressive. In fact, combinations of the two forms may be the most effective way for students to explore different conceptual ideas.

whereby when students were introduced to new representations for problems, their frequency of use for each type of representation increased when searching for solutions. Students appeared to show an increase in representational flexibility (Karmiloff-Smith, 1992) as they found meaning in each of the systems. Tytler and Prain (2007) showed similar findings in science, illustrating that as students construct multiple representations of evaporation, their conceptual understanding increased. They attribute the gains to “a shift in [the students’] capacity to imagine the process whereby water can exist in air, involving the construction of a narrative of causation allied with the spatial representation” (Tytler & Prain, 2007, p. 244). Danish and Enyedy (2006) reported on young children (kindergarten and first-grade) representing pollination using multiple forms. Grounded by the theory of MRC (diSessa, 2004; diSessa et al., 1991; diSessa & Sherin, 2000), the authors present how students’ decisions regarding what to include in representations are influenced by a number of factors that they call Negotiated Representational Mediators. What is deemed important to include in a representation is mediated by classroom conversations, an individual’s communicative goals, the collective goals of the classroom culture, the physical environment, the tools available, and a variety of other factors (Danish & Enyedy, 2006). Essentially, the various resources available to a student impact how that student produces a representation. Additionally, as the student represents an idea across multiple forms, different mediating factors (Danish & Enyedy, 2006) influence different forms of representation. These studies promote a common theme: as students explore concepts through the production of multiple representations, they reason in more sophisticated ways and they ultimately develop a stronger understanding of the ideas in question. However, the results of this work are contingent on a crucial principle for all educational activities, which is that educationally rich activities require posing appropriate questions such that the investigation of a concept in each of the representational forms yields a benefit (Friedlander & Tabach, 2001). For this reason, the specific context for the study proposed for this dissertation has been chosen to elicit multiple representations from participants that will be generative and that will support students in gaining deeper understandings of air and the particle model of matter. The study asked participants to generate representations with the hypothesis that the very act and process of generating these productions would be amplify and transform their own ideas.

Pilot Study: Students' Multiple Representations of Air

In a pilot study, eighth-grade students' ideas about air were explored through their production of multiple representations (Gravel, 2009). In one-on-one interviews, four students used oral language, drawing, stop-motion animation, and the construction of physical artifacts to reason about and explain air. The results of this pilot study revealed a tendency for the students to focus on the material aspects of air in the oral language and drawing, while they attended to process aspects of air when constructing animations. For these students, the shift in reasoning about material substance to reasoning about process was facilitated by the representations they produced.

Initially, students described air as “taking up space,” an idea previously reported in the literature (see Driver et al*.,* 1994; Tytler, 1998). In descriptions of air taking up space, students used relatively imprecise and vague language with regard to the material structure of air. For example, Trish (a female participant) struggled with early oral descriptions of air, possibly because of the “unseen” nature of the substance. She was given the opportunity to interact with a linked-syringe device,[7] and she was asked to consider the compression of air in a syringe. She described compression as, “It’s like…um…like squishing, I guess. Like, I don’t know. It’s weird because it’s like, I don’t know, like you can’t see it except for it’s getting smaller, so it’s kind of weird.” When students were offered the opportunity to put their ideas on paper, they tended to use continuous symbols, like shading or lines (see Figure 2), until they were prompted to critique a particulate representation of air, such as dots on paper to represent air in a closed container (see Figure 6.B).

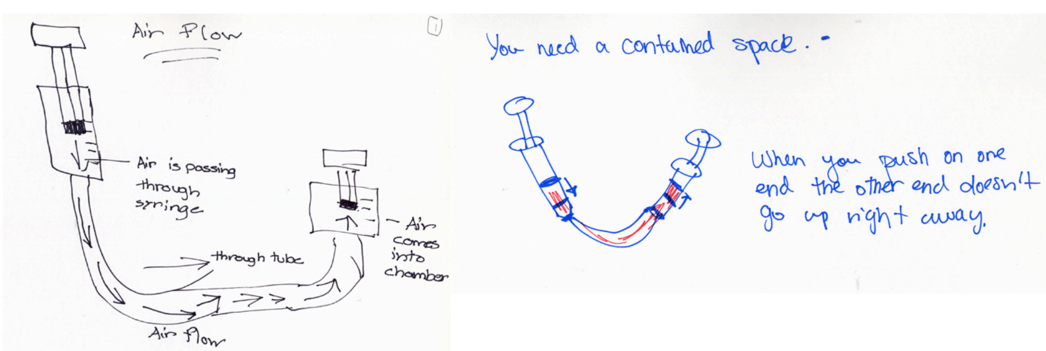

Figure 2. Students’ continuous representations of air on paper.

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[7] Two large syringes with their nozzles connected by a tube; see Figure 5.

The example presented to the students activated their ideas about molecules,[8] and many students began incorporating a discrete symbol for air into their drawings and animations (see Figure 3). As students proceeded to the second interview, they shifted the focus of their utterances to process-oriented ideas; they began to describe possible mechanisms to explain compression, describing linking processes between the causes and the effects they observed.

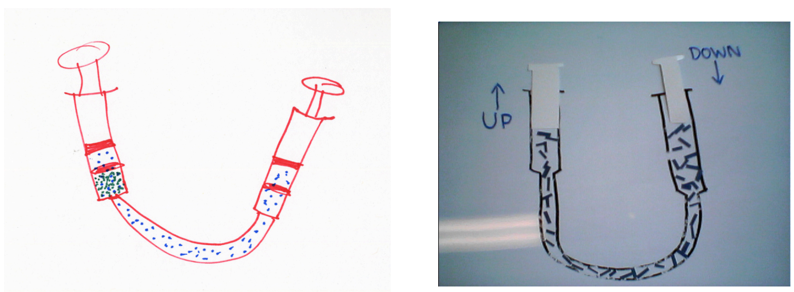


Figure 3. Students' use of discrete symbols in drawing and animation, following the introduction of a particulate representation by the interviewer.

In the final interview, students grappled with selecting physical materials that "stood for" air, and tended to focus on how their representations were similar to and different from "real" air, and how the mechanisms they reasoned about could be captured in their physical constructions.

The data from this pilot study suggest that eighth-grade students reason about material-substance and process aspects of air and the particle model

[8] Not all students adopted a discrete symbol, which was surprising considering the example was offered by the interviewer, a person in a place of authority, and research on testimony would suggest students might more likely to adopt an example put forth by an adult (see Harris & Koenig, 2006).

differently, depending on the external representations they produce (Gravel, 2009). Material-substance ideas may be more prevalent in situations emphasizing oral language and drawing, and process ideas are more prevalent during sessions focusing on animation. However, there are nuances in the data that suggest these relationships deserve further attention. For example, two students (Trish, Amanda) adopted a particle representation (e.g., dots on paper) more quickly than other students (e.g., Fernando). The adoption and appropriation of particular representations is complicated, multifaceted, and an area deserving of future investigation. Furthermore, how the particular forms students generate, critique and refine support and influence reasoning requires more attention as well. For example, students naturally critiqued their chosen physical representations of air relative to their ideas about air itself; they were able to comment on how the cotton balls they chose for air, for example, were similar to and different from "real" air molecules. Such a comparison presents an opportunity for students to reflect on their own understandings and representations of their thinking. The students in the pilot study had been previously introduced to ideas about molecules and the particle model of matter (not in the year in which the study took place, but earlier in their schooling). Thus, the idea of matter being particulate in nature was available as a possible resource for students. How would students who have not encountered the idea of molecules or particles (e.g., through classroom activities explicitly focusing on the particle model) think and reason about air using multiple representations? The results of this pilot study

(Gravel, 2009) formed the foundation of the design of the dissertation study presented here.

To summarize, external representations play a powerful role in transforming human thinking. The production of representations in a multitude of forms presents an opportunity for students to express and reflect upon different aspects of their thinking, while constructing explanations of the mechanisms that underlie their observations. This dissertation aims to explore these issues of representation and students' thinking about air and the particle model.

Chapter 3. Methodology

This dissertation study is a qualitative extended clinical interview study with fifth-grade students. In this chapter, I present the specific research questions, the research setting, the participants, the interview protocol, and the analyses of the data.

The Case for Extended Clinical Interviews

In order to delve deeply into the relationships between students' ideas and the representations they produce, the methodology for this study was designed to provide for detailed and nuanced interactions between student and researcher. Representations are an inherently communicative device, and while conventional systems of representation are socially constructed systems, an individual must learn and appropriate various forms of representation as means for communicating with the external world. In order to unpack how an individual student learns and appropriates representations, and how these representations in turn support reasoning about a particularly complex physical process, the context chosen for this study was one-on-one "extended clinical interviews" (Duckworth, 1996). I consider these interviews to be similar to Eleanor Duckworth's (2005) description of "critical explorations" in the classroom, where students are invited to talk about their ideas with the goal of evolving and deepening their understandings as a result of the interview or exploration. Interviews allowed for the investigation of how students construct verbal explanations of their thinking and how these explanations develop relative to evolving ideas and the production of external representations. Within the interview context, the nuance and detail of how relationships between students' ideas and their representations form, change, and influence their reasoning became the focal point of the research.

Research Setting

The study was conducted at a public charter school in the greater Boston area, which I will call the Ringer School.[9] The Ringer School is a kindergarten through sixth grade school, where 99.1% of students are children from non-dominant communities - students who are African-American, Hispanic, Asian, and Native American (Gutiérrez, 2008), and 31.7% of students are not native English speakers. Nearly 85% of students are considered to come from low-income families, and 85% of students qualify for free or reduced lunch (Massachusetts Department of Elementary and Secondary Education, 2011). The School serves students from many different cities and towns around Boston, and the percentage of stability is 95.4%. It hosts a diverse population of students from many backgrounds and communities, the school culture is strong, and the tendency is for students to remain at the Ringer School for the duration of their elementary school careers.

[9] Pseudonym.

The Ringer School has a focus on science, technology, engineering, and mathematics, and as such it maintains a science laboratory with a full-time science coordinator. Students recruited for the study were interviewed in the science laboratory, with no other students present. Interviews took place in the mornings, before the school-day schedule began, and at the end of the day before transportation arrived or after-school programs began. I believe holding the interviews in the science laboratory was an advantage for this study, as students were in the environment where their typical science investigations occurred. Thus, the setting was a familiar one, particularly for reasoning about and exploring science ideas. The specific science curriculum each student engaged in during the 2009-2010 school year (and in years prior) had not yet addressed states of matter from the perspective of particles. Students may have encountered the word “cell” or “molecule” in other contexts (related to plants or water, respectively), but never in a formal curricular unit.[10] That is not to say that some students were not exposed to these ideas through other activities (e.g., personal exploration, after-school clubs, etc.), but that the students had not been formally introduced to the particle model of matter in the school setting prior to this study.

In addition to the interviews with each participant, I worked closely with all the students in the fifth grade for three months after the interviews took place to learn more about their habits, reasoning styles, and patterns of thinking. My prolonged engagement with the students was delayed until after the interviews, in

[10] Some of the study participants were enrolled in an after-school “science club,” which may have addressed issues of the composition of matter, particles, and a particle model - as the theme of this club was “modeling.”

an attempt not to bias my interactions with the participants based on prior experiences with them. Immersing myself in the classroom environment after the interviews, I believe, better prepared me to be a critical analyst of the interview data and how the students performed in the individual interviews. My work in the Ringer School classrooms provided me with another window into how students in my study approached science in group and classroom settings.

Participants

Participants in this study were recruited from two fifth-grade classrooms at the Ringer School. A letter explaining the research was sent home with all students in both grades, and from the pool of students who returned consent and assent forms, 12 students were chosen at random as participants. Prior to the start of the study, two students not selected for inclusion in the larger study were interviewed to test the protocol and make any necessary revisions. Beginning in December 2009, interviews with the twelve participants began.

Of the twelve students interviewed, seven were female students and five were male students (proportions that mimicked the proportions of males and females at the school). The average age of the participants was 10 years 9.2 months. The participants' pseudonyms are Isis, James, Kandice, Kendra, Nicholas, Norris, Oriana, Oscar, Perry, Sarah, Tasha, and Wanda (see Figure 4).

Figure 4. Snapshots from the interview videotapes of each of the participants.

Extended Clinical Interview Structure

The study was designed to have participants produce and reason with multiple representations on the topic of air. In three consecutive interviews - each lasting approximately 30 minutes, with no more than two days between interviews - students produced representations in different forms. This study is classified as a microgenetic design, involving repeated interactions with the same student over a short time period (Siegler, DeLoache, Eisenberg, 2006). In the first interview, they engaged, for 5-10 minutes in the science exploration described below.

Introduction and exploration

Students were first asked what they know about air before being presented with any physical props. After a brief conversation about these initial ideas, they were presented with a single syringe (see Figure 5) and asked to explore it. Over the course of a few moments, each participant was prompted to describe the syringe and his or her familiarity with the device, as well as any comments pertaining to how a syringe works and what might be inside. Participants were then presented with two syringes connected at the nozzles by a short piece of rubber tubing (see Figure 5).

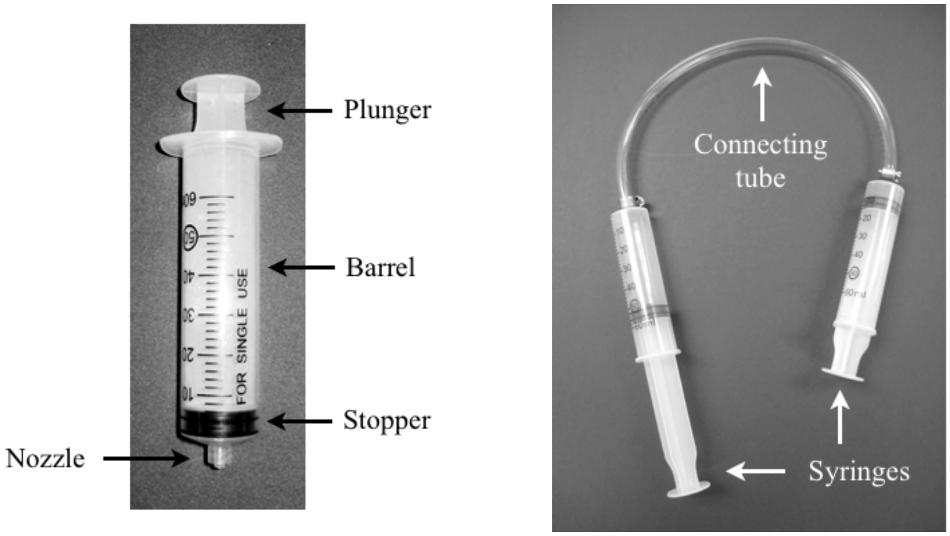


Figure 5. Syringes that were presented to the students in the study. The single syringe (left; parts labeled) were presented first, followed by the *linked syringes* (right).

This device, which I will refer to as the *linked* syringes*,* has been used by other researchers in investigations of students' understandings of air pressure (deBerg, 1995; Séré, 1982, 1986; Tytler, 1998). With this device, three actions can be performed:

1. *Pushing Case:* The plunger of one syringe is depressed causing the plunger of the other syringe to extend.
2. *Pulling Case:* As one syringe plunger is pulled outward, the other syringe plunger depresses.
3. *Compression Case:* Simultaneously pushing both plungers inward results in compressing the air inside the syringes, which is observable by the noticeable change in total internal volume of the system.

The linked syringes provided an exploratory context, where students could interact with the device to explore the cases described above. The syringes allowed for explorations of change over time and compressibility. Given the fact that air is a gas, it has compressibility properties much different from liquids or solids, and I sought to make this capacity explicit in the device chosen as the context for the interviews.

Participants were presented with the linked-syringe exploration in three different interview sessions, which centered on a general question: “What do you know about air based on the linked-syringes?” Each session was a one-on-one extended clinical interview (Duckworth, 1996) in the style developed by Piaget (1929/1965) and later modified by Inhelder, Sinclair, and Bovet (1974), Ginsburg (1997), and Duckworth (1996, 2005; see also Brizuela 1997). The extended clinical interview (or “critical exploration”) “has two levels of meaning: both exploration of the subject matter by the child (the subject or the learner) and exploration of the child’s thinking by the adult (the researcher or the teacher)” (Duckworth, 2005, p. 259). These interviews rely on the use of tasks to elicit student thinking. Ginsburg (1997) highlighted several key features of this method: (1) a protocol of questions as a starting point for the interview, (2) tasks which are specific, (3) freedom to explore lines of reasoning introduced by the interviewee, (4) encouragement of verbal justifications and explanations, and (5) the use of the interviewee’s words (among others). All three sessions used the clinical interview method, wherein the participant was asked to respond to questions about air and how the linked syringes relate to air through four different representations: oral language, drawing, stop-motion animations, and physical artifacts, while offering verbal explanations and descriptions of their productions and reasoning.

Following the initial exploration with the single syringe and the linked syringes, the *first interview* focused on students' oral language and production of a drawing, the *second interview* focused on students' construction of a stop-motion animation, and the *third interview* focused on their construction of a physical artifact. The final activity in each of the three interview sessions involved presenting the student with an identical set of linked syringes containing water instead of air. Air and water are commonly used words, and students have been shown to reason about the two ideas together in different contexts (Lee et al., 1993; Osborne & Cosgrove, 1983; Stavy, 1990). The intent of presenting students with water filled syringes was to highlight the difference in compressibility between air and water, as the water-filled syringes cannot be compressed. The comparison was intended to engage the students with reasoning about the material composition of air as compared with water, about potential mechanisms that would explain compression differences between air and water, and about the quality of their representations for describing the water-filled syringes.

Over the course of the three interviews, students' engagements with the question "What do you know about air based on the linked-syringes?" were video-recorded. For each participant, the three-interview sequence was completed in fewer than seven days, with the majority of interviews taking place within one week.

Interview 1: Producing drawings and critiquing example representations

A precedent for drawing as a form of representation through which students express their ideas about science and mathematics is well established in the literature (Acher & Arcà, 2009; diSessa, 2004; Freeman, 1972; Lehrer & Schauble, 2000a; Piaget & Inhelder, 1971; Sherin, 2000; Vosniadou & Brewer, 1992). In this first session, participants were initially asked what they knew about air prior to being shown the linked-syringe device. They were then shown a single syringe, followed by the linked syringes. Approximately 10-15 minutes of the first session was spent exploring the students' verbal descriptions and explanations of the linked-syringe device. Following oral descriptions, the drawing task was introduced using the above prompt. Sherin (2000) reported specifically on students' Meta-Representational Competence (MRC) with drawing, verifying that students are capable of representing spatial displacements on the referent through two-dimensional drawings. Thus, for the purposes of this study it was a reasonable assumption that students could, at least partially, represent their understandings of air through drawings. In addition, the process of having to put something on paper proved to be a powerful exercise in organizing the students' thoughts and eliciting more pointed explanations. Students were asked to complete a first drawing of their ideas about air and the syringes, using the following prompt: “Could you show on this piece of paper what you know about air based on the linked syringes?" No student in the study spontaneously verbalized ideas about particles or included particle ideas in their first representations (which was expected). After this first drawing, students were asked to generate an inscription showing air inside a closed container (see Figure 6.A). Following this task, all participants were prompted with a picture of a

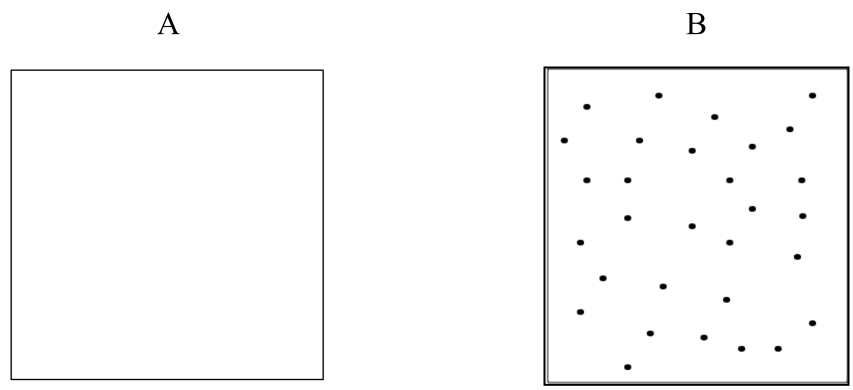


Figure 6. (A) Image of the closed container, or “box,” in which students were asked to generate an inscription showing air inside; (B) Image of “dots on a page” shown to participants as a prompt for exploring their thoughts about air represented as a collection of particles.

rectangular box with dots drawn inside (see Figure 6.B) and were asked, “A fourth-grader showed air to me in this way, what do you think about this?” The reason for using fourth-grade as the age indicator of the fictitious producer of the dots representation was that students are more likely to critique something that they do not consider as the work of an adult or a peer, which could potentially be the “right answer” (Grotzer, personal communication, February 23, 2009; see also Harris and Koenig’s [2006] work on trust and testimony in children). Following discussion of their representations of air in the container, students were asked to generate additional drawings to show the pushing case and the compression case. For each drawing, the student was given a new sheet of paper, except for the cases where students preferred to continue drawing on a single piece of paper.

At the conclusion of the session, students were shown two example drawings, generated by students in the pilot study. One drawing represented air using a continuous symbol (lines; see Figure 7.A), and the other drawing represented air with a discrete symbol (dots; see Figure 7.B). Students were

A B

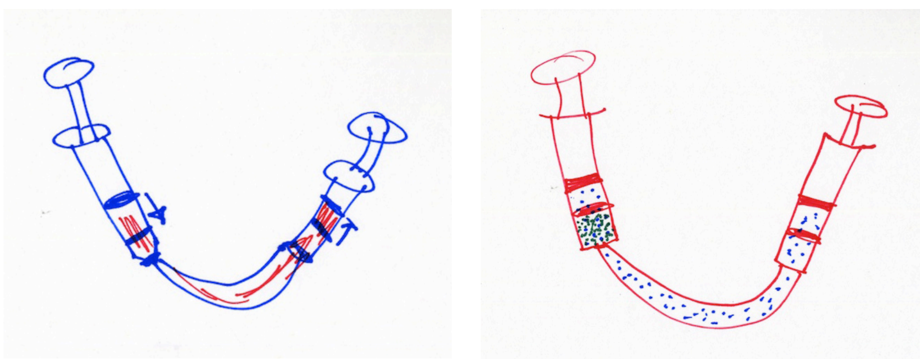


Figure 7. Example drawings shown to participants to elicit critique. (A) Representation of linked-syringes with continuous symbol for air - lines; (B) Representations of linked syringes with discrete symbols for air - dots.

asked to critique the example drawings with the following prompt: "Here are two drawings the fourth graders made, what do you think about them? What do you think they were trying to show?" In addition, they were asked to make comparisons between these example drawings and their own productions. The inclusion of this comparison was motivated by the claim of the Meta-Representational Competence framework (diSessa, 2004) that students possess a native competency to critique representations; students' critiques are another window into their thinking and reasoning about representations of air in the syringes. The intent of presenting the students with example representations (in general) was to explore how they could relate their own productions and reasoning to another production in the same medium. The example representations also created the opportunity to investigate how students may revisit their explanations and representations after interpreting an alternative. Following the critique of the example drawings, students were asked to consider the water-filled syringes and whether their drawings could be used to describe water as well as air.

Interview 2: Student-generated animations and critiques of example representations

In addition to the two more widely used representations just described - drawing and oral language - this study also explored students' productions of less frequently used representations in less conventional forms. Stop-motion animation is one of these less conventional forms. Morrison and Tversky's (2001) "Conceptual Congruence Hypothesis" suggested that since animations depict changes over time, then the situations about which students are asked to generate animations should also include elements of motion and change over time (Schwartz, personal communication, March 15, 2007). Based on this theory, I chose to use the linked-syringes as a dynamic device on which to focus students' explorations. Students generated the animations produced in this study with a tool called SAM Animation (Searl, Gravel, & Rogers, 2009).[11] SAM Animation is an educational software developed by the Tufts University Center for Engineering Education and Outreach (see Appendix B for a description of the software). Bétrancourt and Tversky (2000) define animation as a "series of frames so each frame appears as an alternation of the previous one" (p. 313; see also Ainsworth, 2008). In other words, stop-motion animations are movies comprised of a number of still images that are played in rapid succession. Early non-digital versions of animations include flip-books, where small changes in the depicted scene resulted in more fluid movements when viewed in succession for very short periods of time (typically less than 0.1 seconds between images). In SAM Animation, a web-camera is connected to the computer that displays a live video image in one window of the software. This allows for the user to make the animation out of whatever materials they desire (e.g., drawings, paper cut-outs, LEGO bricks, clay, fabrics, etcetera). The user "snaps" the image that he or she wants, and a still picture is recorded and placed in a time line. The user then adjusts the scene captured by the camera and "snaps" another image. The animation is, therefore, a collection of still images taken from the camera that is focused on some scene external to the computer. The user can then choose to "play" the animation at various frame rates (measured in frames per second). The result is a digital movie, which can be exported as a Quicktime™ file and shared with other students, teachers, and researchers. Previous research on the use of stop-motion animations

[11] Please see http://www.samanimation.com for more information and to download this software.

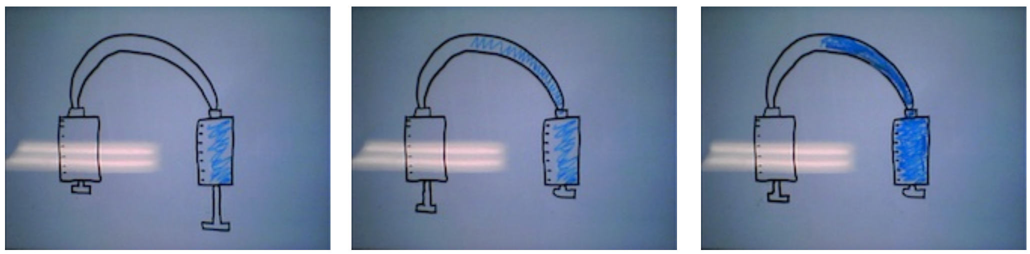
in science explorations has shown it be an interesting and successful medium for eliciting students' ideas (Church et al., 2008; Gravel, 2009; Gravel & Brizuela, 2009). In this session, students were asked to generate an animation about air based on the linked syringes, with the following prompt: "Can you make an animation showing what you know about air based on the linked syringes?" The interviewer assisted the participant by helping to operate the computer software as to focus the student's attention on the representation. The student designed and constructed all elements of the animation, and an interview concerning the contents of the animation was conducted while the animation was being made, as well as after the final animation was completed. This method of construction of an animation with help from the interviewer proved successful in prior studies (Gravel, 2009; Gravel & Brizuela, 2009).

At the conclusion of the animation construction process, each student was presented with two example animations created by students in the pilot study. One animation depicted a solid quantity (see Figure 8) of air coming from one syringe and moving to the other. The second animation depicted air as small dots moving from syringe to syringe, becoming more densely packed under compression. Students were asked to critique the animations. More specifically, they were presented with the examples and given the following prompt: "Here are two animations that a fourth grader made, what do you think about them? What do you think they were trying to show?" In addition, they were asked to compare their animations to the example representations with which they were presented.

Finally, students were asked to consider the water-filled syringes again and whether their animation could be used to describe water as well as air.

Example A

Frame 1 Frame 2 Frame 3



Example B

Frame 1 Frame 2 Frame 3

Figure 8. Frames from example animations presented to students. Example A contains (Frame 1) continuous representation of air, (Frame 2) moving out of the syringe, and (Frame 3) showing compression; Example B contains (Frame 1) the ambient condition with a discrete representation of air, (Frame 2) the pushing case, with the left syringe going down, and (Frame 3) the compression case, with the particles closer together.

Interview 3: Constructing physical representations and critiquing example artifacts

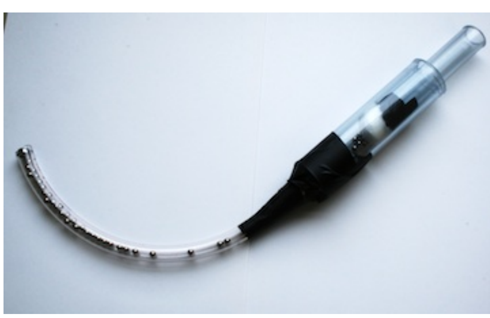
The construction of physical artifacts was the focus of the third interviews, a representational form, similar to animation, infrequently reported on in the literature. Scientists regularly engage in designing experiments, building physical representations of phenomena, and manipulating materials that are tactile in nature. However, students have far fewer opportunities to explore scientific ideas through the construction of physical models or representations. Thus, the process of "building an explanation" is employed in this study as an experimental (although not novel, see Penner, Giles, Lehrer, & Schauble, 1997) approach to eliciting external representations from students about science ideas – in this case, about air. Constructing something that is visible as a way of representing an "unseen" (such as air) may seem contradictory. However, this study's design capitalizes on this very contradiction (i.e., making an invisible visible): the relationship between students' ideas about air and their choices for objects to represent those ideas offers us another window into the relationship between externalization and conceptual understanding.

Piaget and his colleagues in Geneva are known for their tasks (such as the seriation or classification tasks used with young children) for eliciting students' thinking (Gruber & Vonèche, 1977). Borrowing from that tradition and the limitations of relying only on students' verbalizations, physical artifacts were incorporated as the representation students produced in the final interview session. Similar to the Genevan tradition of task-based interviews, Bamberger (1991) described the success of using a technique called "Reflective Conversation," where the researcher questions the subject while the subject manipulates tactile materials to solve a problem. Bamberger addressed the challenges of understanding students' unspoken decisions and nonverbal representations of their understandings in physical situations. Students often make decisions without being able to articulate the rationale, for example, when they try to balance a number of objects on a scale. When asked to explain how they know how to balance the scale, students will often respond, “I just knew,” offering little insight into what they are thinking. Bamberger (1991) used the Reflective Conversation to get at the “going-on” of the activity, constantly questioning the students about decisions, steps, or processes to gain another perspective on how the child is representing his or her knowledge. Researchers often show students demonstrations (not explorations, as this study did) and ask for their explanations, but rarely ask students to construct physical objects as representations of their understanding. Based on Bamberger’s Reflective Conversation, the final session in the interview protocol involved participants building artifacts that demonstrated some aspect of air based on the syringe exploration. They were given the following prompt: "Can you build something that shows what you know about air or some aspect of air based on the linked syringes?”

The materials included for this task were carefully selected with the intent of scaffolding students’ explorations to serve the goal of developing a final artifact that the students could feel represented their understandings. The materials were piloted and found to be flexible enough to accommodate a number of approaches, while successful in eliciting representations from students with which they were satisfied (Gravel, 2009). By working with carefully selected materials, students hold a better chance of producing artifacts with which they feel comfortable, or even proud. Instead of giving students a limitless supply of materials, they were first asked to write a list of what materials they would like to use. Once they had arrived at some idea, they were allowed to explore the provided materials (see Appendix A) to begin constructing their artifacts.

As the students tinkered with materials and began to construct their devices, they were questioned about their choices, ideas, and reasoning. At the conclusion of the session, students were shown two images of example artifacts built by students in the pilot study (see Figure 9). Each artifact highlighted different ways of representing an aspect of the linked syringes, and the participants were asked to critique these artifacts. They were given the following prompt: “Here are pictures of two things built by fourth graders, what do you think of them? What do you think they were trying to show?” In addition to critiquing these artifacts, they were asked to compare their own construction with the example representations.

Example A



Example B

Figure 9. Images of example physical artifacts constructed by students in the pilot study to explain air and the syringes, which were shown to each participant.

Finally, as with the other interview sessions, students were presented with the water-filled syringes to discuss their physical constructions in the case of water-filled syringes as well as air-filled syringes.

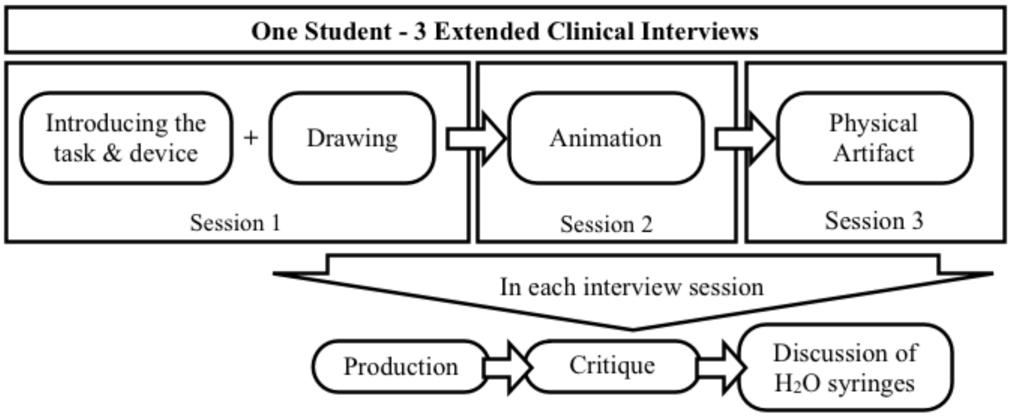


Figure 10. Diagram illustrating the sequence of interviews for each participant. Verbalizations were collected from all three sessions, as well as the productions in each form – drawings, animations, and physical artifacts.

To summarize, each participant engaged in three sessions (illustrated in Figure 10), where the representations under investigation included oral language and drawing in the first session, animation in the second session, and the construction of physical artifacts in the third session. Each session concluded with the students reviewing a prepared representation for their critique and a comparison of their representation of air to the water-filled syringes.

Data Collection

All of the interviews were videotaped, audio recorded, and transcribed to ensure that the verbalizations of each session were captured; all participants were assigned pseudonyms. Each of the productions was collected and catalogued in the following manner: drawings were digitally scanned, animations were copied and exported as frame-by-frame compilations, and physical artifacts were photographed from multiple angles. The dataset for each participant consists of a portfolio of oral representations (also referred to as verbalizations or verbal explanations) from each of the sessions as well as productions in the forms of drawings, animations, and physical constructions.

Analyses

The aim of this study was to explore children's ways of representing air when successively producing different forms of representations: drawing, animation, and physical artifact (all of them accompanied by oral language). As such, the analyses involved thick and rich descriptions of each participant's trajectory through the three-interview sequence. As was done in a prior pilot study (Gravel, 2009), descriptions of each participant's journey through the interviews were generated in the form of case studies, to begin analyzing the challenges and successes the students faced while making sense of air and the particle model. From these summaries, one case study was developed in Chapter 4 to: (a) characterize elements of the student's understandings of air and the particle model of matter, (b) describe the evolution of scientific ideas throughout each of the sessions, and (c) identify the role that external representations played in supporting reasoning and fueling the construction of explanations for the observed phenomena. This case study is an intentionally lengthy and detailed analysis of the student's work in the three interviews, offered with the intent of providing valuable contextual details that assist considerations of the specific issues presented in the subsequent results chapters. In keeping with the qualitative tradition (Charmaz, 2006; Maxwell, 2005), validity and trustworthiness of the data hinge on the researcher's interpretation of the interview as well as the researcher's ability to effectively communicate these findings to the reader. The case is not meant to be representative of the dataset as a whole, but rather illustrative of trends in the data and potential areas for further investigation.

Following the creation of the case studies, two results chapters (5 and 6) were formed around two central themes: (1) students' ideas and reasoning about compression in the linked syringes, and (2) the diverse trajectories and representational practices of students in their attempts to make meaning of the unseen substance, air. Trends across students were analyzed and are presented in each chapter to reveal nuances and details of the complex relationships between students' ideas and their representations.

Chapter 4. Multiple Representations of Air: A Case Study of Isis

This chapter presents a case study of one student, Isis, that addresses each of the research questions from the perspective of one student's efforts to represent and explain her ideas about air. The case study offers a rich description of Isis' ideas, representations, and reasoning about mechanisms.

Introduction

Isis is a ten year-old African American student in the fifth grade at the Ringer School. Her teachers describe her as curious and articulate, with a particular affinity for mathematics and science. In my time interviewing Isis and working with her science class, I observed her engaging with and exploring scientific language as she made meaning of the phenomena she encountered. She is curious about how the natural and artificial worlds work, and she was quick to mention her relationships with her sisters – who, as Isis claimed, are successful students and science enthusiasts in their own right. She is a student who enjoys doing science – experimenting, exploring, and "messing about" with explanations and ideas. This tendency coupled with her affinity for scientific language made her trajectory through the interview study interesting and illustrative. I would not classify Isis as a participant representative of the study population; however, I believe this case offers an interesting example of how a 5th grade student accesses and uses her resources in particular contexts. As will be made evident in this case study, Isis is quite adept at using both school-based ideas as well as everyday experiences as resources for generating explanations and creating representations of her thinking. Our sessions occurred on three consecutive mornings, and the account of Isis' reasoning, her production of external representations of air, and her evolving verbal explanations are presented herein (and represented in Figure 24 - included at the end of this chapter).

Session 1 - Verbal and Drawn Representations

When asked about what she knew about air, Isis said that it was a gas and that humans need air to live and breathe. She recalled that air is made of "oxygen stuff" that humans breathe and explained that air is all around us in the atmosphere. Like all of the students in this study, Isis' examples of air were related to wind and memories of wind moving things such as trash on the playground and her lunchbox, which was blown off a wall by wind earlier in the week. She was comfortable talking about air in its different capacities, but at the same time curious about how these ideas may fit together.

When introduced to a single 60 milliliter syringe, Isis said she could pull air into the syringe, "because air is everywhere," by pulling back on the plunger (thus causing air to flow into the syringe through the nozzle). When asked how she knew air was in the extended syringe, she said she could hear air exiting the syringe when she depressed the plunger. Thus, even though she could not see air, the mere fact that she could "hear" it was enough evidence for her. Her initial ways of thinking about air appeared to be a blend of experiences interacting with the substance (e.g., wind, hearing air move), and more school-like notions of "oxygen"[12] and the statement that "air is everywhere," said in a matter-of-fact tone. For Isis, her trajectory through the three interviews is characterized, in part, by this blending of what I will call "school ideas," or token uses of scientific labels (see Perkins & Grotzer, 2005), with the ideas she recalled from prior experiences.

Isis was presented with the linked-syringe device, and asked to explain what she thought might happen when one syringe was pushed.

> *Isis*: Yeah, because all the air from here goes through the tube and into here, and it's just like the same amount of air bounces back and forth [between the two syringes].

Isis realized that the linked syringes contained a constant volume of air ("the same amount"). She was asked to predict and explore the pulling case and explained what she observed by saying, "Because it's sucking all the air from here [the syringe with the extended plunger] into this [the syringe where the plunger was being pulled out]." Isis evoked a "sucking" mechanism (a common explanation found in the literature, see Hammer, 2004), which I interpret to be related to her understanding of the device containing "the same amount" of air that travels from syringe to syringe. As she mentioned, the "air bounces back and forth" and that tendency allowed her to explain both the pushing case as well as the pulling case.

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[12] Also a terms frequently found in popular press, such as newspapers, magazines, and television (see Best, Dockrell, & Braisby, 2009)

She was asked why air is able to push things, and she introduced a scientific term as means for describing her experiences with wind:

Interviewer: And how come air is able to push on things?

Isis: Because it has...force, I think?

Interviewer: It has force? Okay. What do you mean by force?

Isis: Like, it [air] has power, like we were saying with the wind.

Isis used the words “power” and “force” interchangeably as she began constructing verbal explanations for why air can push things. Her uncertainty with the particular words, as evidenced by her pause and her interchanging of force and power, indicated her interest in using scientific language to reason about the syringes. In other words, she used specific vocabulary (like “force” and “power”) to begin articulating an explanation. Isis went on to reason about air pushing in relation to her ideas of quantity of air (“the same amount”) in order to make sense of compression:

Interviewer: So, what do you think is happening here [the compression case]?

Isis: All the air is going to here [points to middle of connecting tube]...and then it has to push back.

Interviewer: All right, so how come when we push [both syringes at once – compression case] our fingers stop? How come there's a point we can't push any more?

Isis: Because all the air, like, all the air doesn't fit in it [the syringes and connecting tube]. So now they have to push back.

Interviewer: So, when we let go, how come they move backwards? What's making them push back?

Isis: Air.

Interviewer: How so?

Isis: Because all the air from both of these [the syringes] go into the tube, and then when you have your stopping point, it's because all the air, like there's too many. There's too much air in the tube [connecting tube], so when you let go all the air [from both syringes] it bounces back to where it was before [when not being compressed].

As with other students in the study, Isis' reasoning about the compression case hinged on the quantity of air ("there's too many") and a lack of space ("all the air doesn't fit") in the connecting tube. Isis' explanation contained an implicit idea that each syringe contained an amount of air, and the combined volumes ("all the air") was "too much" to fit in the tube connecting the two syringes. The result was the push she felt on her hands (caused by air's resistance to compression) and eventually the rebound of the plungers when they were released. Isis suggested that there is a constant quantity of air ("the same amount"), but it is unclear whether she believed the volume of that quantity remained constant, or whether it changed under compression. Additionally, Isis predicted that water-filled syringes would behave like the air-filled syringes, where the plungers would move in when compressed and "bounce back" when released. The model of two quantities (either of air or water) occupying and filling a fixed space (i.e., the connecting tube) explained her ideas about the compression case at this point in the interviews; reasoning that "too much" in the connecting tube caused the plunger's "stopping point" was a sufficiently detailed explanation for Isis. Following the discussion of compression, she was asked to put something on paper explaining what she knew about air and how the syringes work.

Isis was hesitant to draw at first, and she claimed she was better at writing than drawing.[13] After some encouragement, she decided to focus on drawing the

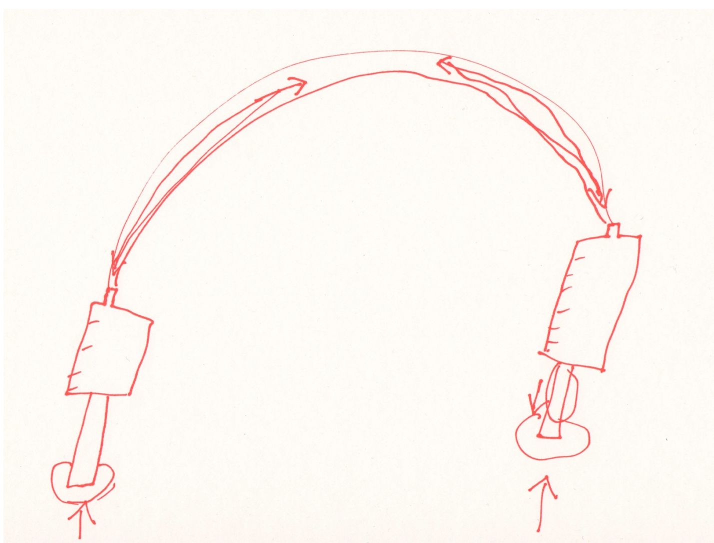

Figure 11. Isis' first drawn representation - depicting the compression case with the air-filled syringes.

[13] This is an interesting admission, considering her affinity for scientific language and vocabulary.

compression case first. Isis' explanation of compression as two quantities of air meeting in the tube to generate the "bounce back" became part of her drawn representation (see Figure 11), as well as her verbal explanation of what she produced.

> *Isis*: All the air goes into here [connecting tube], and then right when all the air meets, it has to bounce back, and then that's [the "bounce back"] what pushes this [the plungers] back down.

Isis offered a more detailed (despite her usage of "here," "that," and "it") description of compression when explaining her drawing, using arrows in different ways to highlight elements of the compression case (see Figure 12). She

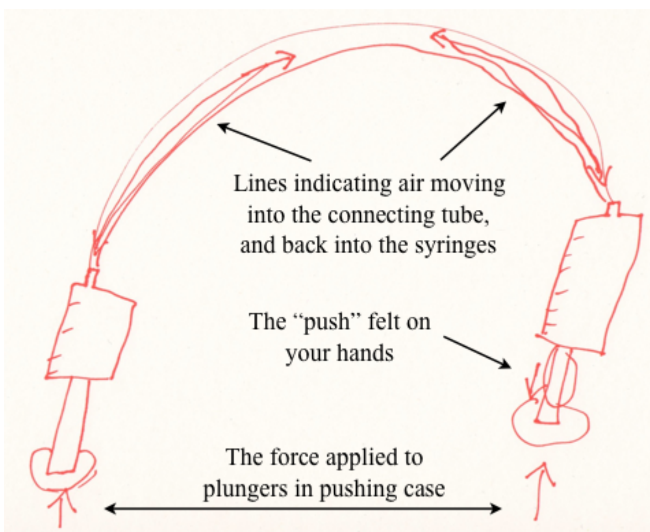

Figure 12. Arrows of Isis' first drawing, labeled with comments describing what each arrow was intended to show (based on her verbal descriptions).

first drew arrows pointing upward underneath each of the plungers to indicate, "We're pushing both of them" (arrows showing a "push"). Then she added lines with arrows starting at each of the syringes and moving toward the middle of the connecting tube (arrows indicating movement and direction). At this point, she said, “And then right when all the air meets, it has to bounce back,” during which she drew lines originating in the connecting tube going back down into the syringes, with arrows to indicate direction (arrows showing movement and direction). Finally, she said, “And then that’s what pushes this back down,” while circling the plunger on the right-hand side of the drawing and adding a downward facing arrow (arrow indicating the “push” one feels on the plunger handles, see Figure 12). Isis used lines, arrows, and verbal descriptions to reason about and explain the compression case. Just as language and scientific phrases had helped Isis organize her verbal explanations before the drawing task, here she used inscriptions to further organize her explanation. In a sense, the effort to capture the verbal explanation on paper made elements of the problem more salient for Isis; her drawing made explicit the major components of her verbal explanation (and presumably her model for how compression worked): two quantities of air, the lack of space in the tube for the two quantities, and a “bounce back” once the quantities have “met in the middle.” Isis was asked to consider what happened “in the middle,” where she believed the air “met.”

> *Interviewer*: And so what's happening right here [in the connecting tube] where it all meets? What do you think it looks like right there?
>
> *Isis*: Well, you can't really see air.

Isis' "you can't really see air" response, while interesting, is relatively predictable given that asking students to draw something they cannot see is a challenging task.[14] To some degree, claiming that, "You can't really see air" excused her from having to choose (or invent) a symbol for something that is unseen; claiming that "you can't really see air" was the path of least resistance. However, when prompted to try representing air, students in the study tended to overcome their initial hesitations of generating an inscription for an *invisible*, and they created some representation of air itself or a way to explain the way in which air moves. In Isis' first drawing of the compression case (see Figure 12), she used lines to show the movement of two quantities of air and she also used arrows, which appeared to have more than one meaning. To probe her reasoning about the syringes and her representations of air at this point in the interview, she was asked to show on paper what air would look like in a closed container.

Figure 13. Isis' drawing depicting air inside a closed container.

[14] It is interesting to note that Isis had no trouble talking about something she could not see (i.e., air), but that generating an inscription or symbol for air posed more of a challenge.

Before she put a marker to the paper, Isis suggested using “colored water instead of air” to make the unseen quantity of air visible in some manner. She was prompted to try putting something on paper, and she drew a cloud-like symbol with the word “air” written inside. She continued to express discomfort or distrust with the task of representing an unseen; Isis said she was concerned that someone viewing her drawing would not know what her idiosyncratic inscriptions may mean, which is why she included the word “air” in her drawing, “just in case they [the viewer] didn’t know” (see Figure 13). Her reluctance to generate an inscription for air as a substance appeared to stem from her awareness of the communicative aspects of representation; she seemed distrustful of the ability of an invented inscription to effectively communicate her ideas about air. However, when she was presented with the *dots on paper* representation of air (see Figure 6.B), with no text labels, viewing it immediately activated an idea for Isis.

Isis: Oh yeah! Because of the...um...’cause in science we were talking about...I forgot what they were called, I think they're called molecules?

Interviewer: Okay. So, you think these would be showing, like, air molecules?

Isis: Yeah, and when you have it in, like, ice, they don't move around a lot. When you have it in water, they kind of move around a lot, and when you have it in a gas they move around a lot.

The dots clearly made her think of molecules, but like her use of the words "force" and "power," her use of this term may have been what Perkins and Grotzer (2005) refer to as a "token use" of a scientific phrase. In other words, Isis used phrases like "force" and her description of molecules and particle movement (presumably learned in a prior formal science experience[15]), while the canonical meanings of these phrases may not have been available to her. The descriptions of molecules moving appeared to be a phrase she was repeating (quite adequately) after having heard it elsewhere, thus, serving as a placeholder as she developed her ideas about compression. More importantly, the phrase served a more valuable purpose in priming her with the idea of air being made of discrete parts. In this instance, she did not adopt a discrete representation of air, perhaps because she was still concerned with the communicative aspects of this form.

Interviewer: So, do you think this (see Figure 6.B) is a good way to show air?

Isis: Ye...yeah. [looks hesitant]

Interviewer: What's not good about it?

Isis: I don't know, because like, it's just dots. What if like a kindergartener came up? They wouldn't know what the dots meant.

Isis' resistance to the dots representation seemed to be fueled by her communicative commitments; others may not perceive dots as standing for air

[15] Isis had mentioned "learning this in class" earlier in the interview; the "this" presumably being the idea of molecules.

molecules. One possible explanation for this could be that in the presented example (a container filled with air), the dots did not present Isis with an explicit advantage over writing the word "air" to show the presence of air. In other words, drawing a cloud labeled "air" met her implicit goal of communicating the contents of the container to a potential audience (a goal which may have become explicit through her critique of the example). I hypothesize that not until a specific need (such as for communicative purposes in the articulation of a particular mechanism) arises for molecules as a way of thinking about air would Isis consider adopting and appropriating this discrete representation.

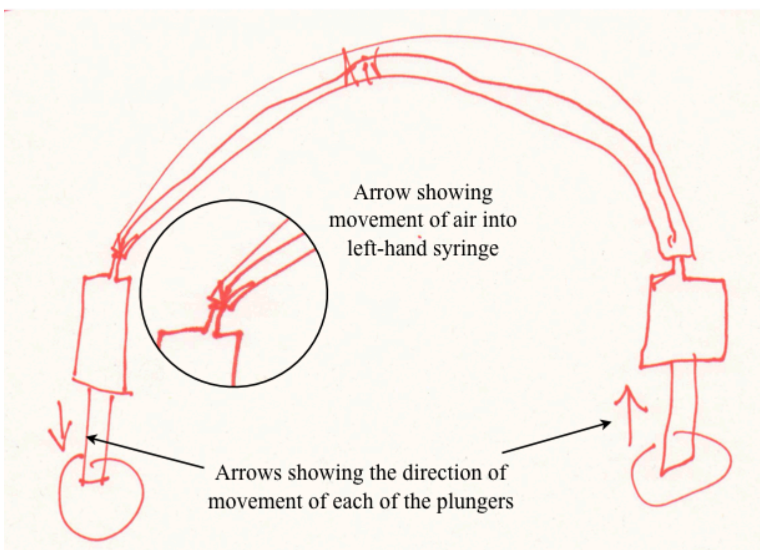

Figure 14. Isis' second drawing showing the pushing case, with annotation describing the intent of each symbol (taken from her verbal statements).

Isis generated a second drawing, in which she re-represented both the pushing case and the compression case. Her depiction of the pushing case (see Figure 14) showed a line labeled "air" going from one syringe to the other (see top middle of drawing), with associated arrows showing the direction that each of the plungers moved. Despite now being aware of the *dots* representation, Isis continued to use lines to show air. A possible interpretation for this is that a line demonstrates how a substance moves from one point to another to represent the change she observed, and thus dots were no more effective for communicating motion than lines. When asked to re-draw the compression case (see Figure 15),

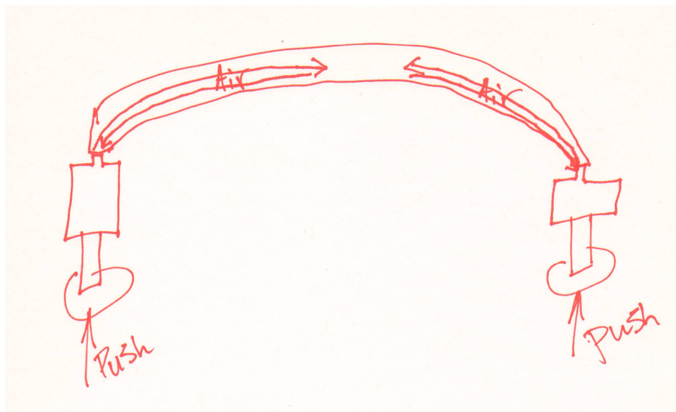

Figure 15. Isis' second attempt at showing compression in a drawing - using arrows and written words to highlight elements of the problem.

Isis used lines again in a similar manner to the way she showed it originally (in Figure 11). This time, she added written labels, presumably because she had imagined an audience for her representation, and because she wanted to make the implicit ideas contained within her production explicit to the viewer.[16] Isis

[16] The protocol specifically disregarded introducing an audience to the participants. For example, the participants could have been told that they were generating a drawing for a classmate, teacher, or parent. However, rather than introduce a specific audience, the design of the study allowed for explorations into whether and how students incorporated audience into their representations. For some participants, the audience became an explicit element of the representation, while others left audience as an implicit feature of the representation. This is an object of further study that was not specifically analyzed in this dissertation.

finished outlining the syringes on paper, and then began narrating as she added lines and labels to her drawing.

Isis: K, so, when you...[begins writing on drawing], when the air from here [coming from the left syringe], meets up with the air from here [coming from the right]...and then when they meet, they have to bounce back to where they came from.

Interviewer: What's making them bounce back to where they came from?

Isis: Because…the tube can't hold that much air.

Interviewer: Okay...

Isis: ‘Cause it's just like pressing all this air into something that won’t fit it. Just like trying to fit a bunch of water into a small cup.

Isis’ second drawing of the syringes led her to elaborate on the idea of air not being able to “fit” into the connecting tube (there being “too much” air from both syringes, as she said earlier). Her elaboration consisted of a “cup and water” analogy, which served to partially clarify her description of the compression case by giving her something tangible (i.e., water) to compare with air. Earlier in the session, Isis mentioned that one could not see air and she suggested using water as a means for showing air (“maybe you could like take colored water instead of air”). The unseen nature of air posed a deeper challenge than simply inventing an inscription to stand for air on paper; it required reasoning about a way to conceive of air as a substance.

While the literature suggests that many students at this age do not believe air is a material substance (Driver et al., 1994; Séré, 1985), I contend that within the context of the linked syringes and making sense of compression, Isis' beliefs about air were made more explicit through the process of representing her thinking and establishing new connections between ideas. While she did not use canonical ideas about air (e.g., air has mass) to make sense of compression, she was able to reason about how air can be compressed by focusing on the quantities of air and relating this to water. Isis' use of water, which is a visible substance, to reason about air, which is an invisible substance, was facilitated by the compression context. Her analogy of water fitting in a cup was a way of reasoning about quantities of air being "too much" for the connecting tube. The challenge for Isis then became how to create a link between her ideas about quantities and a means for representing those ideas on paper. I contend that her earlier use of the term "molecules," which was prompted by the interviewer's *dots on paper* representation, made the idea of discrete parts of air more accessible to Isis; molecules and the notion of changing volumes helped her to think about compression.

Interviewer: Okay. It doesn't want to be in there [connecting tube between syringes]? So, when I do this [compression], what happens to the amount of space that's inside there [the linked syringe system]? Am I making it bigger or smaller, or does it stay the same?

Isis: It goes smaller, but then right when you let go, it goes back.

Interviewer: So, how are we able to make air smaller? How does that work?

Isis: Well...you're just compressing it.

Interviewer: Okay. What does that look like? How come air can be compressed?

Isis: Because...it's like...I can't, I don't know, it's hard to explain.

Interviewer: What do you think if we could zoom way in, what would it look like to compress air?

Isis: Think it would look like all the molecules coming together [makes gesture showing hands with fingers spread out coming together, similar to a clap, see Figure 16].

Interviewer: Okay. Do you think you could show me that?

Isis: Kind of like how the fourth grader did it [using dots - referencing having seen Figure 6.B].

Considering changes in volume[17] provided Isis with a bridge between her ideas about quantity and a discrete representation (i.e., dots) of air. The change in the volume of air contained in the linked syringes required Isis to reason about a

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[17] Granted, she never used the word "volume," and likely was thinking more about quantity and amount of space (see Chapter 5).

possible mechanism to help her explain compression, “all the molecules coming together.” She used a particular scientific phrase - talking about molecules in a

Figure 16. Isis’ gesture showing “all the molecules coming together.”

general sense related to gases, solids, and liquids earlier in the session - and she began unpacking those statements to make sense of this particular context. Her gesture appeared to help her conceive of molecules or “dots” coming together when air is being compressed - an idea she then represented on paper.

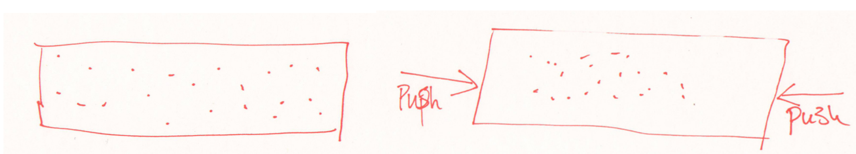

Figure 17. Isis’ *dots* representations to show air molecule spacing in ambient air (left) and when air is being compressed (right).

After Isis produced her drawings of molecules in compressed air and ambient air (see Figure 17), she constructed a verbal explanation beginning with the compression case.

Isis: ...And then I imagine them come together...kind of like with dry ice.

Interviewer: With dry ice? What do you mean by that?

Isis: Because dry ice changed from a solid to a gas. So, when it's in a solid, all the molecules, they're not moving a lot. But then, once like, it starts getting warm, all the molecules spread out and it becomes a gas.

Interviewer: Hmm, interesting.

Isis: So, that's kind of what we're doing. But it's not going to become a solid.

She followed up her explanation of compression with an explanation of the ambient air (i.e., when neither of the plungers were being pressed; see Figure 17 - left).

Isis: They'll just be spread out and all over the place. And, like, they would have their own space.

Isis' drawing (see Figure 17) and these two verbal explanations of molecules spaced differently under compression and "when we're not pushing" (i.e., ambient air) are a compilation of many ideas (or resources) working in concert to reason about air in the syringes. The idea of molecules was introduced early, but was not something Isis was comfortable representing on paper with a discrete symbol (such the *dots* introduced by the interviewer). Earlier in the session, Isis recalled molecules and molecule spacing in different states of matter; however, these descriptions appeared to be token explanations that were not directly applied to making sense of the syringes. Thinking about compression, specifically, created a need for describing what changed about air when it was compressed that allowed the volume to decrease. In other words, she realized the cause (compression case) and effect (change in volume), but she needed to develop a mechanism or linking process to connect cause with effect. Isis first reasoned about volume using a specific quantity of water fitting in a cup. I hypothesize that the focus on quantity (refining her ideas of "too much") led Isis to create links between molecules, molecule spacing, and a dots on paper representation of air to arrive at a sophisticated verbal explanation and drawn representation (see Figure 17). The context of making sense of compression with air in the linked syringes resulted in Isis reasoning with quite complex ideas about a mechanism for how air can be compressed. Yet, the application of these ideas to water-filled syringes highlighted the instability and limited reach of her *dots* representation and her ability to reason about molecule spacing, at this point in the interview sequence.

Isis was shown the water-filled syringes, and was asked to explore how they worked in comparison with the air-filled syringes.

Isis: It's [water-filled syringes] really hard to push.

Interviewer: Yeah, does it move in [do the plungers move in]?

Isis: Well, like, one of those lines [gradations on the syringe chamber].

Interviewer: How about compared to the air?

Isis: The air, I think, is like more flexible, kind of.

Interviewer: More flexible, tell me a little more about that.

Isis: 'Cause the air...it's like if you had a flexible person and a not flexible person. They could touch their toes, but the other person couldn't. It's kind of like this one [water-filled syringes] can move just a little bit, but that one [air-filled syringes] can move a lot till it's at its limit.

Isis introduced the concept of "flexible" to describe the difference between air and water. When she first experienced the incompressibility of water in the syringes, she said it was "really hard to push." Her means for explaining this "hard to push" feeling was relating that sensation to a person who is not "flexible." Isis created an analogy where a flexible person (who "could touch their toes") was like air, and an inflexible person (who "couldn't" touch their toes) was like the water. Interestingly, earlier she used molecule spacing to explain compression in the air, and she also mentioned molecule spacing in liquids as compared with gases. However, her reasoning about compressing water did not include ideas about molecules. In other words, the dots as molecules representation appeared locally constrained to one material (i.e., air) or context and had not been abstracted as a means for talking about multiple materials. The resources Isis used to make sense of compression in air were different, in part, than those used to make sense of the water-filled syringes. Isis was explicitly asked to think about water using the ideas about molecules she had raised earlier.

Isis: Um...water, it's a liquid, and air is a gas. So, the molecules for water are a little bit more close than with air.

Interviewer: So, do you think that has to do with the flexibility?

Isis: [nods head yes] Because how you could turn water into a solid is by freezing it, not by pressing it.

Isis began her explanation by using the scientific phrases she had used earlier, "The molecules for water are a little bit more close than with air." Yet, comparing molecules in water and air led her to say that the way water becomes "a solid is by freezing it, not by pressing it." I interpret this statement as Isis' attempt to relate compression in air - which makes molecules "come together" - to what compression *could* do with water (i.e., make the molecules "come together"). Furthermore, I interpret her statement about turning water into a solid as her reasoning that if compressing water made molecules "come together," then it would make water a solid. However, with Isis' way of thinking about this situation, pressure is not a valid mechanism for turning a liquid into a solid. She was asked to elaborate a bit on her statement about water freezing, and she replied, "I keep on thinking about dry ice, but that's made of something else."[18] The session exhibits a complex relationship between the resources Isis used to reason about air - scientific phrases, experiences with wind, analogies about flexibility and quantities of water - and her representations - drawings with arrows and text labels, gestures, and interpretation of a dots model. She demonstrated an ability to work with changing ideas and evolving representations to reason about

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[18] It could be that Isis recalled a connection between carbon dioxide gas and pressure creating solid CO_2, however, her reasoning about this idea was not probed any further. Additionally, her search for connections (e.g., to dry ice) is an interesting indication of her varied attempts to make meaning using the resources she has available.

and construct explanations for what she experienced with the linked syringes. At different points, either her graphic representations (or representational criteria - e.g., the communicative intent of a drawing) or her use of scientific phrases served as bridges to help her make sense of how air can be compressed. Her agility working with contexts and ways of framing the problem to reason and produce personally satisfying explanations is indicative of the power that invention and refinement of ideas and graphic representations can have on students' attempts to find meaning in science. As Isis' explanations gained coherence and sophistication in the second interview session, the power of representations becomes more salient.

Session 2 - Generating a Stop-Motion Animation

In the second session, Isis was charged with making a stop-motion animation of what she knew about air and the linked syringes. She began by expressing interest in showing air in the "tubes" (i.e., the syringes and connecting tube); she wanted to recreate what she had produced in her drawings - using lines to show the movement of air. However, she recalled the dots representation, "like the other kids did," and opted for trying that symbol for air in her animation. Isis first drew the syringes on a white board with a series of dots showing air in the entire length of the tube connecting the two drawn syringes (see Figure 18). She offered a verbal description, similar to that in the first session, of the air moving from one syringe to the other, pushing the opposite

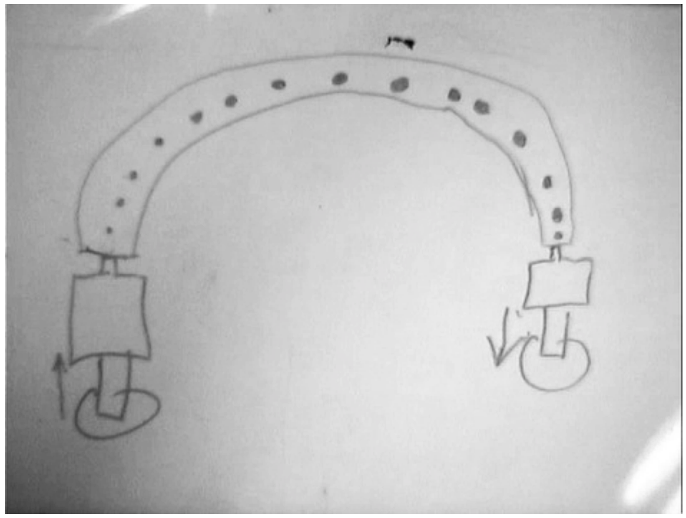

Figure 18. Isis' drawing of the linked-syringes on a white board, prior to beginning her animation.

plunger down. This first step of drawing a static image of the linked-syringes appeared to be an indicator of her uncertainty with the medium of animation; the ability to produce a number of frames which became a motion when played. When Isis was asked how she might change what she drew frame-by-frame to demonstrate how the air moved, she grew eager to begin. I believe her drawing on the white board served as a planning step, where she was able to externalize some of her thinking and to articulate her thoughts about how to generate the animation. After she had organized the problem with a static drawing, she erased this and spent the next five minutes creating seven new frames showing a small number of dots moving forward through the tube in each frame (see Figure 19). Isis specifically chose dots to represent molecules, she said, and went on to elaborate on her animation.

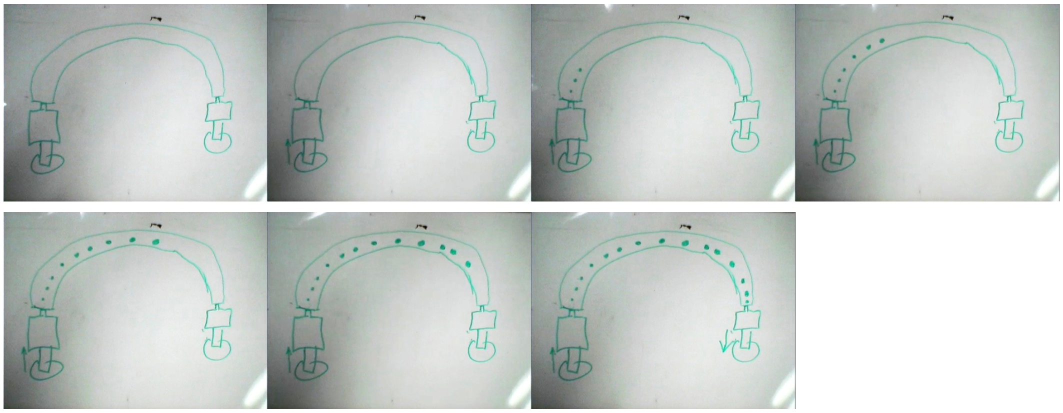

Figure 19. The first seven frames from Isis' animation showing the pushing case with air-filled syringes.

Interviewer: So these [the dots in the animation frames] are showing the air molecules?[19]

Isis: Yeah, because, and I made them a little bit spread out because air is a gas, and gas molecules are really spread out and liquids are kind of spread out, but solids are really close together.

Interviewer: So, do you think this is how many air molecules are in there [inside the syringes], or would there be more of them [air molecules]?

Isis: Probably more.

Interviewer: Probably more? And do you think they are this big [points to dots in animation], or are they smaller than that?

Isis: Much, much, much smaller.

Interviewer: Can we see them?

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[19] She declared the dot symbols were showing "molecules" while she generated the animation.

Isis: No.

Isis seemed to be more comfortable representing an unseen in this session than in the previous session. She appropriated the dots symbol in her animation, and this representation allowed her to focus on describing air molecules in a more specific sense - referring to their size and the relative number of molecules in a given quantity of air. Despite her continued use of scientific phrases about molecules (which may not have been fully understood), such as her reference to gases, liquids, and solids in response to why she chose dots, the dots representation served as a means through which she could reason about molecules, specifically; the idea of molecules and the embodiment of that idea in the dots representation served to amplify Isis' thinking. Her reasoning was further probed by asking her to consider how air could push on things.

Isis: Because there's the same amount of air in this [syringe with plunger open - left-hand side in her animation - see Figure 19], and then...when you push all of the air through the tube into this one [the opposite syringe - right hand side], it has to make room, so it pushes this one down [right-hand plunger].

Her explanation of the pushing case, facilitated by her animation, was concise and made use of the "same amount" argument that she had used in the previous interview session. For Isis, the air from one syringe is pushed "through the tube" and "into [the opposite syringe]," where that closed syringe (on the right-hand side in her animation; see Figure 19) must "make room," so the plunger extends.

Interestingly, this explanation does not make use of molecules or the dots representations in any unique way. That is, the dots she drew as a discrete representation of air appear to relate to the molecule-like quality of the substance, rather than how a collection of those molecules may move, collide with each other, and transmit forces (e.g., pushing on the opposite syringe).

Following her description of the pushing case, Isis was asked how she might show compression in her animation, and she offered the following idea:

> Isis: Okay. So, if you push on this [left-hand syringe] and push on this [right-hand syringe], all the air from there [left-hand syringe] comes over here [into the connecting tube], and all the air from this [right-hand syringe] goes over here [connecting tube], and then when it gets too tight over here [the air in the connecting tube], it has to move back over here [into the syringes].

Her description of the compression case mirrored what she said during the first session, except for the phrase "too tight" as a means of describing "all the air" going into the connecting tube. In the previous session, she had said there was "too much," and a shift to the phrase "too tight" may be the product of her "flexible" analogy raised at the end of the first session. The idea "too tight" refers to both amounts and relative spacing, which is a more sophisticated, multidimensional idea than her previous "too much" idea. After offering this description of compression, Isis added six frames to her animation to show a process of dots leaving each syringe frame-by-frame, and meeting in the middle

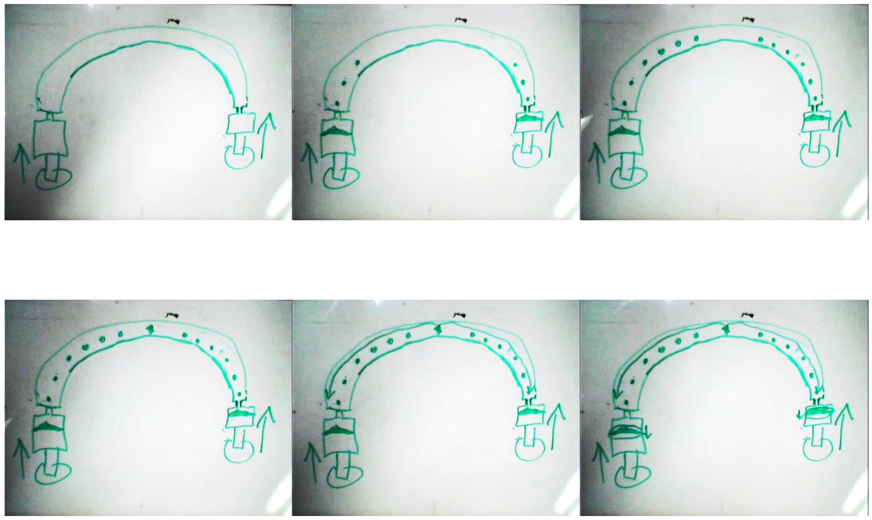

Figure 20. Frames from Isis' animation showing the compression case with air in the linked syringes.

of the tube (see Figure 20). Isis' animation showed two distinct quantities of air moving from each of the syringes into the connecting tube, where they, as she said, "met" and "moved back" to the syringes. Her commitment to dots was probed a bit further, and Isis said that the dots she drew are bigger than air because these dots were "just showing the air." She appeared more comfortable with the model-like nature of the dots (i.e., that they were "standing for" air, not necessarily capturing *everything* about air), which was further evidenced by this exchange:

Interviewer: Okay. Do you think the dots would be moving around in there, or do you think they would be kind of standing still?

Isis: Moving around.

Interviewer: Moving around? What do you think makes them move?

Isis: ...because...well, I don't really know that. But...I think it's because gas is like, it's like more flexible than a liquid. Because when we used the water, when you would push on both of them it didn't move as much as the air.

Having adopted the dots representation, Isis was able to reason about molecules in relation to the differences she witnessed trying to compress air and water.

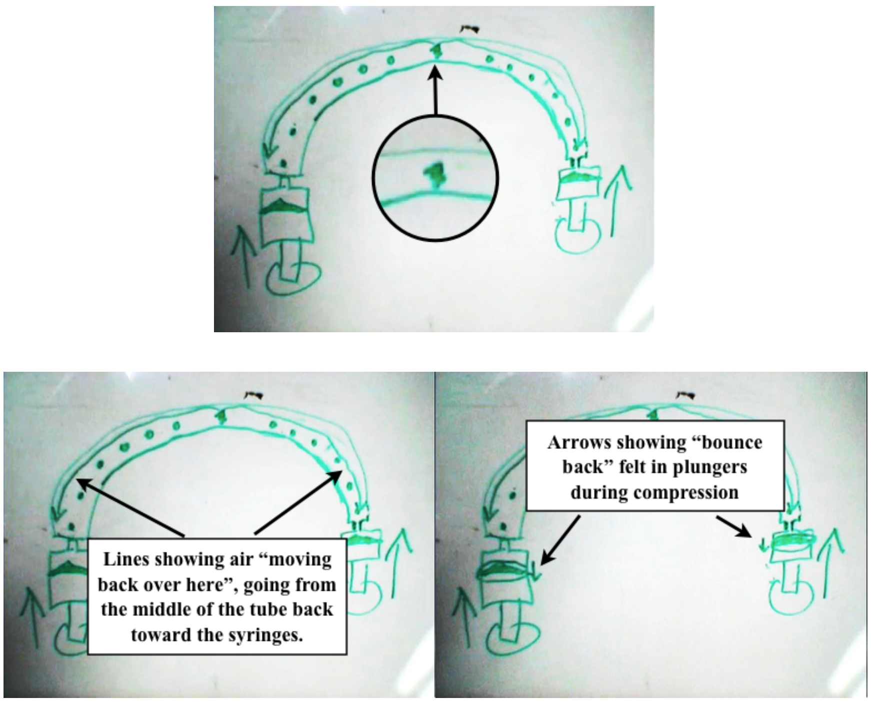

Figure 21. Frames from Isis' animation showing what happens when air "meets" in the middle under compression, and "bounces back" to each of the syringes (annotations added to show symbols in the animation).

The dots symbol provided her with a representational bridge between her construct of "flexible" and thinking about air in terms of molecules moving and molecule spacing in water and air. Her depiction of two quantities of dots moving into the connecting tube and "meeting" in the middle was particularly interesting (see Figure 21). She made an inscription at the midpoint of the connecting tube in the shape of a star, and she proceeded to add lines with arrows extending from the star back toward each of the syringes. Finally, she added small downward-facing arrows at each of the syringes to indicate the "release," which pushes the plungers back out of the syringes. She gave a more detailed description of this part of her animation.

Interviewer: And then tell me about that little thing that you drew in the middle?

Isis: That's when it gets to, like, it's tightest point, and then it has to release.

Interviewer: Okay...And, the release is what you showed with the arrows going back?

Isis: Yeah.

Interviewer: And, so, is it the release that's making these move back down when we let go?

Isis: Yeah.

Interviewer: Describe that for me a little bit.

Isis: Because when all the air gets too tight in the middle, it has to find a way to exit out. And...since these are all the way up here, it has to push itself down to make room.

Isis reiterated her "too tight" idea from before, and she was asked to elaborate on this notion.

Interviewer: So, what's a way you could show us “too tight”? What do you mean by that? What's changing?

Isis: Like, it's all [the air] coming close and close and close together.

Interviewer: Okay...So, do you think these dots are actually getting closer together?

Isis: Maybe...

Interviewer: Maybe?

Isis: A little bit, but not much. It's just like when all the air...’cause, you can't like...if you have too much air in one thing, like if you have too much air in one thing, it'll pop. So, it's kind of like this [the compression case]. When it [the linked syringes] had too much air in the tube [connecting tube], you had to release it.

Interviewer: So, the air doesn't like to be squished together?

Isis: No.

Interviewer: Okay. And, it wants to be a bit more spread out. Why do you think that is?

Isis: Because...air needs to go around everything, to make everything live.

Isis refined her reasoning about air molecules under compression, supported by her adoption and appropriation of a dots representation and the creation of her animation. Whereas her use of ideas about molecules earlier (going back to the first interview session) may have been placeholders, now she was able to reason about molecule spacing, the size of molecules, and she began constructing an explanation for why the plungers "release" after compression. She evoked the idea that air "needs go around everything, to make everything live," which I interpret as her initial attempt to explain the at-rest case, where the syringe plungers are not being pressed. An interpretation of Isis' reasoning is that since air is "everywhere," and one of the primary ideas about air is that it helps humans breathe and plants live, then it returns to the at-rest condition because it simply needs to be "everywhere". Ultimately, Isis developed representations (first in drawn form, and here in animated form) that allowed her to progressively refine her verbal explanations of how air behaves in the linked syringes. Her adoption and appropriation of a representation of molecules served to support her reasoning about molecule spacing and compression, which she was then able to apply to reasoning about the water-filled syringes.

Isis suggested that in an animation showing water being compressed, the plungers would not move inward (as they did with air), and the dots showing water molecules would be closer together than with air. Isis not only used this particle idea for gases, as some literature suggests students do more easily (Driver et al., 1994; Pozo & Gómez Crespo, 2005), but Isis also considered liquids from the standpoint of molecules. When asked to compare air and water, she said:

Isis: It's more hard [the water filled syringes].

Interviewer: Why do you think that is?

Isis: Because...water is not as flexible as air, because all the molecules are closer together.

For the first time in the interviews, Isis combined the idea of molecule spacing with her "flexible" construct to offer a more articulate explanation of why water and air have different levels of compressibility. Building on this short statement, Isis expanded on flexibility in relation to molecules when she said:

> What I mean by flexible is like, 'cause gas is all the molecules like floating around and they've got their own space, and the water, it's not as spacey as that. So, it's kind of like, more packed. Like, it's kind of like if you wear tight jeans. It's kind of hard to move in them. But if you wear your size jeans, it's easy to move around.

As Isis elaborated on the "flexible" idea, she now included a molecule-based description to explain what she meant by flexible. As she explored this idea verbally, she generated another analogy wherein water was like "tight jeans" that are "hard to move in." Using her animation as a resource for making meaning of compression, Isis explored and refined her verbal explanations by generating analogies (e.g., flexibility of a person in the first interview, tight jeans in this interview) that helped her think about the problem. Not only was she able to reason about her own representation and explanations of the syringes, but her critiques of the example animation with which she was presented also became more precise and sophisticated.

Isis: [shown Figure 8 - Example B - depicting air as dots] She's [assumed creator of example animation] showing the air by the molecules I think again, but she kind of made them a little bit tight, like they're more spread out.

Interviewer: So, do you think it does a good job showing air, or is maybe this a better way to show water? Or is it in between [partly good for showing air, partly good for showing water]?

Isis: I think that it would kind of be a better way to show water.

Interviewer: Okay. So, here's the next one [Figure 8 - Example B - showing compression].

Isis: I think she's showing when you push on both of them [the plungers].

Interviewer: Okay, So, let's start here at the beginning, she's showing one [plunger] going down and one going up [the opposite plunger].

Isis: Yeah, and then at the end she does both of them [shows compression].

Interviewer: And what happens to all the little molecules of water or air?

Isis: They get tighter and tighter and tighter.

Interviewer: What do you think about that?

Isis: I think that's the same thing that I was saying, because they get all close together, and then they have to spread out again.

Interviewer: And what's making them spread out?

Isis: Um...the air?

Interviewer: Yeah, what's making the air spread out again?

Isis: Because...it's kind of like a spring.

Interviewer: Okay. Tell me a little more.

Isis: 'Cause if you put it [the spring in relation to air] all close together, and then you let go, it bounces back to where it was before.

When shown the air-as-dots example animation (see Figure 8 - Example B), Isis believed it showed air, but that the spacing between particles was too tight. As Isis continued to reason about why the plungers "bounce back," she introduced a new idea relating this "bounce back" of the syringes to that of a compressed syringe. She did not explain the spring idea further; however, her spring analogy is an example of perhaps a newfound stability in her relationships between air and molecules. To elaborate on her ideas about compression, she generated an alternative idea in the form of the analogy to springs. Armed with the resources of a discrete model of air and water, a means for describing compression, her own animation, and an example that she could critique, Isis made significant strides reasoning about air. The integration of these resources resulted in her constructing a mechanism that explained compression, and she was able to reason about and relate this mechanism for compression to other ideas that she considered to be similar (i.e., springs).

The second session was marked by Isis' adoption and appropriation of a dots model of air that provided her with means for reasoning about compression. The third and final session required Isis to make a leap from representational forms with which she had grown more comfortable - drawing on paper, drawing on a white board for the animation - to building a physical representation of her ideas about air in the syringes.

Session 3 - Constructing a Physical Artifact

Isis began the final session by expressing a desire to build something to show both the pushing case and the compression case; she remained committed to a dots (or "discrete parts") representation of air.

> *Isis*: Well you know how some kids drew dots? Maybe we could use, like, kind of like play dough or something and stick it on the tube. So it looks like air.

As she began to look through the provided materials (see Appendix A), she became fixated on a bag of marbles, as "they could show the molecules." She found sections of clear plastic tubing that she wished to place the marbles in, but they proved to be too narrow to accommodate the marbles' diameter; instead, Isis chose to use metal ball bearings (much smaller in diameter than the marbles) to stand for air. After some tinkering with the materials provided, Isis eventually constructed a device (see Figure 22) that had an inflated balloon at one end of a long piece of clear tube, containing twelve metal ball bearings, with a deflated balloon at the other end.

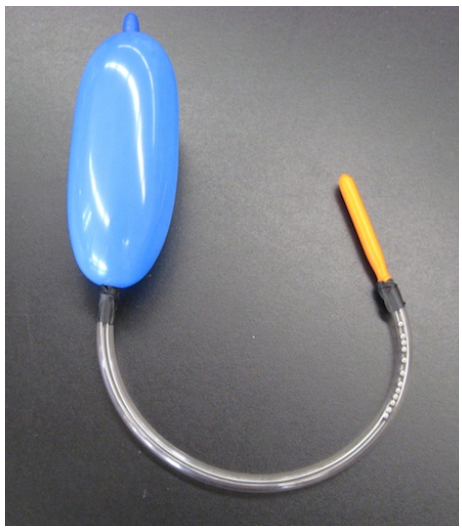

Figure 22. Isis' first construction involving two balloons connected by a clear plastic tube containing metal ball bearings.

Much to Isis' surprise,[20] the inflated balloon did not inflate the opposite, deflated balloon. Puzzled by this finding, she was asked to explain what she had anticipated would happen.

Interviewer: So, imagine it did work, tell me what you think would happen.

Isis: I think all the air from here [in the inflated balloon] would go and kind of push the balls [metal ball bearings] over and

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[20] And to the surprise of the interviewer as well! The force of an inflated balloon pushing air out and through the tube was not great enough to inflate the opposite balloon; in part because of the elasticity of an un-inflated balloon and the nonlinearity of the rubber material.

probably a couple balls would go into here [deflated balloon], and it would blow up this balloon [the deflated balloon].

Interviewer: And how come they [the ball bearings] wouldn't go all the way up, over here [deflated balloon]?

Isis: 'Cause I think the air doesn't have enough pressure.

Interviewer: Say a little more about that.

Isis: 'Cause like, cause all those balls would probably be a little bit heavy cause they're pretty heavy, each one. So, I don't really think just air would be able to move it, and just this amount of air [touches the inflated balloon].

Interviewer: So, you said that these [ball bearings] could show the air molecules, so are these [ball bearings] similar to air molecules or are they kind of different?

Isis: They're a lot different, because they're close together, but that's just because they're balls and they roll around.

Interviewer: Ah ha, what else is different about them?

Isis: They're really big compared to the molecules.

Interviewer: But what's kind of the same about them? Or what's similar about them?

Isis: That they both are the, 'cause they both are kind of like a ball. And like, um, they show that there is air that moves through, I guess.

Isis' selection of ball bearings to stand for air molecules provided her with an opportunity to critique her representation while also making explicit some of her assumptions about air molecules. In other words, the act of describing how ball bearings are "not like" air molecules made some of her implicit beliefs explicit: the ball bearings in her model were larger and closer together than in air, but the roundness of the ball bearings was similar to the way she conceived of air molecules. Given that students have been found to posses a natural competency for critiquing representations (diSessa, 2004; diSessa & Sherin, 2000), it is not surprising that Isis was successful at articulating the differences between air molecules and ball bearings. And, in doing so she made salient her beliefs about air molecules in a manner that may have been more difficult without the analogous case. The model Isis built also focused her attention on how air pushes on something, "pressure" as she called it. Realizing the relative weight of the ball bearings, she contemplated how to alter the device so that the amount of air from the balloon would noticeably impact the ball bearings (i.e., push them). Isis replaced one of the balloons with a balloon pump, and while this inflated the opposite balloon the ball bearings failed to move as she envisioned. Flummoxed by this perceived failure, she began experimenting with parameters of her device to makes sense of why the air was not pushing the ball bearings.

Isis: See, the balls don't move still.

Interviewer: That's what you thought, right? Why do you think that's happening?

Isis: Because, like, the air doesn't have enough pressure and force...

Interviewer: It doesn't have enough pressure and force? What do you mean by that?

Isis: Like because, those balls are big and heavy, and then it's just air, like this little bit of air...

Interviewer: I see, because they're heavy you'd need a lot more air to push them?

Isis: [nods head yes].

To confirm her intuitive explanation for why the air from the pump failed to move the ball bearings, Isis placed a straw containing a single ball bearing at the end of a pump. When air was pushed out of the pump, the ball bearing was propelled across the classroom. This evidence confirmed her suspicions about pushing, and she was then asked to consider compression.

Interviewer: What happens to the little, ah, little metal balls in the tube when you do that [the compression case]?

Isis: They all get really close, and they [air molecules] don't really like being that close in a gas, so they have to, like, release so they all have room. And so that's why they push back down.

Interviewer: Why don't they like being close?

Isis: Because...it's like, when you have a solid all the molecules are really tight and compact. And then, when you have a liquid they're kind of close, but not that much [utterance], but when you have a gas they have to have their personal space.

In the previous session, Isis reasoned that air molecules spread back out because air needs to be around everything; a requirement of living things is having air to breathe. However, in this session, she refined her explanations to begin talking about molecule spacing in relation to some of the phrases about states of matter she used earlier. Isis was asked to say a little more about the idea of "personal space."

Interviewer: So, what's making them want that personal space?

Isis: Because like...like sometimes gases, like they move all...they move through the air. 'Cause that's like what I said, they're more flexible. And instead of water. And then, since it's flexible because all the air molecules have their own space. Kind of like a small pair of jeans, like you can't really move in them. But if they were at least your size, then you can.

Her jeans analogy and the idea of flexibility reappeared in this explanation, as Isis began to connect the many fragmented ideas she had used previously in the session. Her reasoning consisted of molecule spacing in air compared to water, how air is “flexible,” and how that flexibility is a product of larger molecule spacing (i.e., lesser density) in air than in water, whereas water was like a tight pair of jeans and thus not very flexible. She continued to use her construction to explain her thinking.

> *Isis*: We're getting it [air] all together. Putting all the molecules really close, but then like...
>
> *Interviewer*: So, when they're all lined up in the tube like this, what's that like?
>
> *Isis*: It's kind of like a solid.
>
> *Interviewer*: Okay. So, then when we...I can try and make them spread out a little bit, like that, what's that like?
>
> *Isis*: That's...more like a gas...

This exchange highlights not only Isis’ use of the idea of molecules, but also how her constructed representations led her to begin unpacking her explanations to reason further about air under compression. As the interview progressed, Isis eventually replaced the pump with a single syringe that resulted in an iteration of the original balloon-tube-balloon device (see Figure 23), which operated on a

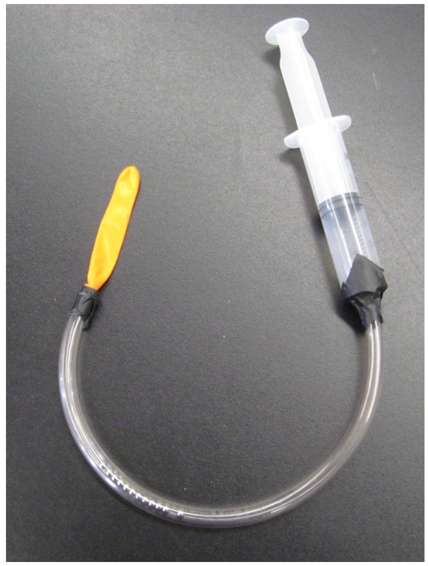

Figure 23. Isis' final construction of a physical artifact showing her ideas about air and the linked syringes. The device contained a balloon attached to a syringe by a plastic tube, which contained metal ball bearings "showing air molecules."

fixed quantity of air, like the linked syringes. With the balloon on the left-hand side inflated and the plunger completely depressed, Isis was asked to predict what would happen if we let go of the syringe plunger. She said, "I don't really think anything is going to happen." This answer was surprising, but I interpret it to be related to the prior failures with the balloon. When the syringe plunger was released, her prediction was confirmed, and the plunger did not move up. However, when the pressure was put on the balloon by squeezing it with her hand, Isis found that air moved into the syringe and began to raise the plunger. She described this as a "little bit of air" moving "slowly" through the tube to the other side. The ball bearings were not pushed by this small quantity of air moving passed them, and as such Isis remained a bit disappointed with her device. She suggested:

Isis: I think if we put water in this and in the balloon, it would be easier.

Interviewer: It'd be easier if we had water in there?

Isis: Yeah.

Interviewer: How come?

Isis: 'Cause, like, water balloons are much easier to like...

The lack of movement with the ball bearings between the balloon and the syringe detracted from Isis' interest in her creation. I interpret her suggestion to replace the balls with water as indicative of her desire to show movement of the material inside the linked syringes. Regardless of her perceived failure, the device Isis built allowed her to reason about air molecules at a deeper level, and to critique the example representations with ideas she honed while working with the ball bearings.

Interviewer: What do you think they were trying to show?

Isis: I think that they were showing here [Figure 9 - Example B], was like if you had the two syringes, all the balls represent the molecules and if you push them, all the balls get together.

Interviewer: Oh. Okay. They did a good job showing the same kind of thing you were talking about?

Isis: Yeah, but it kind of looks like a solid, too.

Interviewer: Why?

Isis: ‘Cause there's a lot of molecules.

The example presented to Isis (Figure 9 - Example B) looked very different from her own, yet she immediately identified the parts of the system (“the two syringes”) and the use of “balls [to] represent the molecules.” She easily interpreted what the model had intended to show and instead focused her criticism on the spacing between molecules. Isis did not like the example, because the representation of molecule spacing reminded her more of a solid than a gas. She was asked to critique the other example as well.

Isis: I think that they [Figure 9 - Example A] were just ... [interrupted]... I think what they were trying to show here is kind of a pump, so they put like a tube like this tube, and then they just like showed all the air going to this side.

Interviewer: So, you think the ball, the little metal things were air there too?

Isis: Yeah.

With this example, she again had little problem identifying the parts of the model and what it was trying to show. Her ability to comprehend and critique the examples highlights a certain comfort with representations of air and the linked syringes that was not demonstrated in the drawing session - where she expressed discomfort with generating an inscription for air. Ultimately, this final interview allowed Isis the freedom to explore air, representations of air, and representations of the syringes using her resources for reasoning that were honed in the prior sessions; some resources (the concepts of "flexible," "molecules," and molecule spacing) proved more productive in her efforts to explain what she experienced than other. Once she adopted a discrete model of air (i.e., air as molecules, represented by dots or ball bearings), she shifted her thinking to molecule spacing, size, and how molecules are arranged differently in air and water. Isis' representations were not only resources for making sense and articulating verbal explanations, but the process of producing these artifacts led her to generate analogies and employ scientific phrases, both of which where useful in developing her explanations of mechanisms to describe the behavior of the linked syringes.

Discussion

The case study of Isis reveals a complex interplay of everyday ideas, school-science language, and the production of external representations; it is an example of the variety of resources students use to reason about and generate explanations of phenomena they observe. Everyday ideas about air - wind, wind pushing things, breathing - served as a starting point for Isis' reasoning. These everyday ideas became explicit in her verbalizations and drawings, and served to initiate a process of refining ideas and subsequent representations to eventually arrive at a rather sophisticated description of air in the syringes (see Figure 24 for a graphical representation of her ideas, utterances, phrases, and representations throughout the interview sequence[21]).

Isis' trajectory[22] through the microgenetic interview sequence illustrates the resources one particular student used to make sense of and reason about air. She used everyday ideas (e.g., "flexible," "tight jeans"), new symbols and representations (e.g., the dots representation), and scientific phrases (e.g., ideas about molecule motion in gases, liquids, and solids) to generate explanations of air. Simultaneously, she generated external representations that (a) supported the construction of these explanations, (b) motivated her to generate analogies and other means of describing her ideas, and (c) ultimately served as embodiments of her ideas that supported her reasoning about air.

Her particular use of scientific phrases about molecules was an interesting occurrence. While these phrases may not have been used with conventional meaning at first, they served as placeholders as she developed more precise descriptions of phenomena like the compression case. The particular ideas contained within these phrases also served as resources for when conflicts arose between ideas she reasoned about verbally and inventing ways of capturing these ideas on paper or in animations. An example of this was the discussion of how a constant quantity of air can occupy a smaller space. In that instance, the use of dots as "molecules" provided Isis with a means for describing "compressing" as

[21] The diagram showing Isis' trajectory reflects a linear progression, however, this is merely a means for presenting her case and it not necessarily intended to suggest that her progression followed a linear trajectory.

[22] I use "trajectory" in a similar sense to how Wiser, Smith, Doubler, and Asbell-Clarke (2009) use the term "learning trajectory," see Chapter 6 for further discussion.

the space between dots getting smaller; these phrases (or words, like "molecule") served to bridge her representations with ways of reasoning about air pushing or being compressed. Beginning with the idea of "flexible" as means for describing difference in compressibility, through the production of her animation using a dots representation of air she was able to reason about flexible in terms of molecules. The combinations of her idea, a discrete representation, and the scientific phrases (regardless of how normatively they may have been used) fueled her sense-making efforts. These scientific phrases that Isis employed included ideas about molecule spacing that supported her reasoning about a mechanism to describe the underlying process between observed causes (pushing both plungers to create the compression case) and effects (the plungers stopping and compressed air pushing them back out again). The ideas contained in what may have been token uses of phrases at first served to bridge her ideas and representations, which facilitated the construction of increasingly coherent verbal explanations (and in turn, the representations she later produced).

Another interesting finding of this case study is the relative stability of the links or relationships generated between Isis' representations and her ideas about air. As an example, consider the *dots* representation, which was introduced to her in the first interview session (the "dots in a box" drawing, see Figure 6.B) and eventually adopted and appropriated in all three interviews. When Isis produced a drawing of her ideas about compression (see Figure 15), she first used a line to represent air inside the syringes. Her descriptions of compression as "too much" air in the connecting tube was captured verbally, but the lines she used as symbols for air did not explicitly communicate this idea of “too much”; her lines showing the motion of air in the pushing case (Figure 14) looked similar to her lines showing compressed air (Figure 15). As previously noted, her use of lines appeared to sufficiently communicate the motion of air. Isis did include a peculiar marking in her drawing of compression, though, which was the space between the two lines (shown in Figure 15). By intentionally leaving space between the two lines of air, each coming from one of the syringes, I argue that Isis was indicating some difference in the compression case. The space illustrated whatever changed about air under compression, and she created the analogy of water in a cup to begin explaining this change. As she attempted to further explain this change in air (by the gesture shown in Figure 16), the alternative symbol presented to her in the “dots in a box” example (see Figure 6.B) provided her with an opportunity to refine her representation. I contend that representing an idea like “too much” with a linear line is difficult. The change in volume of air under compression was not sufficiently explained with “air as lines,” and this led her to appropriate the dots symbol in an invented representation of particle spacing in air (see Figure 17).

Isis successfully appropriated the dots representation to explain her ideas about compression. However, while she generated this way of thinking about compression with air - a mechanism involving particle spacing - her attempts to make sense of water being incompressible did not evoke a use of dot or particle spacing; this inconsistency highlights the stability of her initial appropriation of dots and her reasoning about a mechanism for compression. An explicit connection between the usefulness of particles for explaining compressibility in air and the use of particles to explain water's incompressibility was not established in her initial appropriation; instead, Isis used the idea of "flexible." As she repeatedly represented compression, in her animation and again with physical constructions, Isis was able to apply the idea of molecules - as embodied in her representation - to this air-water comparison, which was a major accomplishment. As the association between her ideas about molecules and the dots representation became more stable, not only with air but other materials like water, Isis was able to reason more coherently about compression. Furthermore, her comparison of a spring to compressed air is indicative of an understanding of some mechanism linking cause (pushing the plungers) and effect (compressed air) that allowed her to generate alternative examples. The combination of the linked syringe context, new representational forms, and an iterative process of production and refinement all contributed to Isis' ideas becoming increasingly coherent, eventually developing into more sophisticated explanations. There is no reason to believe that Isis' journey of representing and explaining her thinking would end after this short, microgenetic interaction; the production and refinement cycle could continue indefinitely. Generally speaking, as students learn to represent their ideas, they become more accessible for further clarification and refinement. The new ideas that spawn from putting one's ideas on paper (or in other forms) can then be re-represented, and this process promotes continued refinement of one's thinking.

This case study of Isis does not clarify whether ideas precede the construction of representations;[23] what the results do suggest is a constant interplay (as captured in the Chart below) between Isis' production of external representations and her developing ways of thinking about air in the syringes. Regarding the research questions guiding this study, Isis' case demonstrates the richness and complexity of ideas represented through her productions; it provides evidence to begin unpacking relations between her explanations and the physical representations (drawn, animated, and built) she produced; and, it shows the evolution of her explanations. The case study highlights how the production of multiple representations influenced her reasoning about air in the linked syringes. This story of Isis illustrates a number of central findings that will be explored in more detail in the following two chapters. Chapter 5 reports students' ideas about compression and how they evolved as they drew, animated, and constructed representations of their thinking. And, Chapter 6 highlights the diversity of ways in which students progressed along this path of thinking, reasoning, and representing their ideas about air. All results and findings are discussed at length and in relation to the particular research questions of this study in Chapter 7.

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[23] Further research is needed to begin unpacking whether ideas lead representations, whether representations help to formulate ideas, or whether a more integrated structure exists where ideas and representation are inseparable. This issue is taken up in the Discussion - Chapter 7.

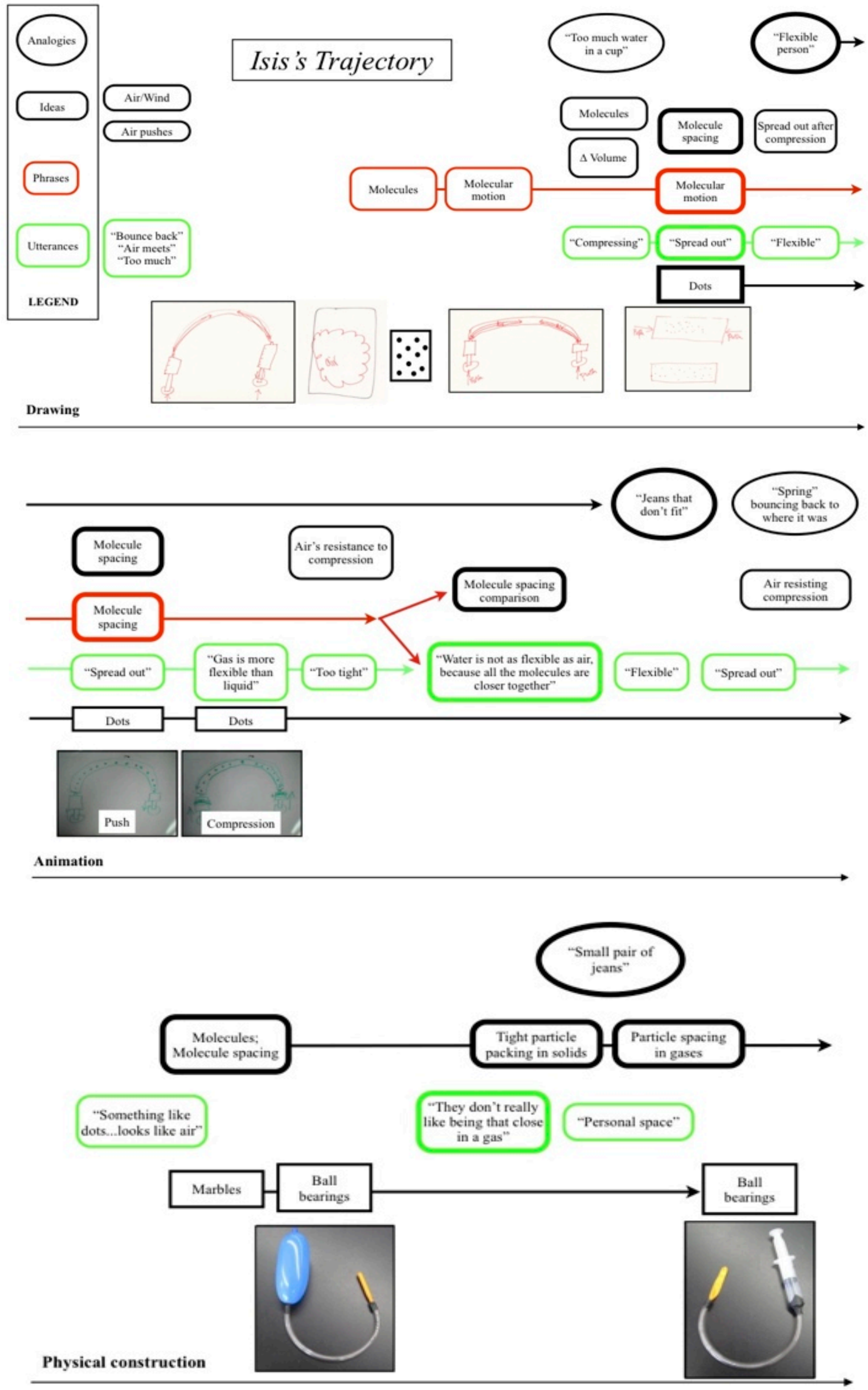

Figure 24. Diagram showing the evolution of Isis' explanations for air through her oral, drawn, animated, and built representations. Her trajectory begins in the top left corner, progressing to the right and continuing through the bottom half of the page. Arrows indicate ideas that were built on as she developed a more coherent explanation of air and compression.

Chapter 5. "*You can't see nothing...but you know there's gonna be a gap*": Students' Shifting Reasoning about Compression Reflected Through their Multiple Representations

Making sense of complicated processes - such as compression in gases - requires complex reasoning practices that span many different modalities (oral language, gesture, external representations, etcetera), and require the use of many different resources. This chapter presents results in the form of students' productions and utterances that illustrate how the use of frequent, iterative external representations in multiple forms - oral language, gesture, drawing, animation, physical artifacts - facilitates students' reasoning. I specifically address research questions 2 and 4: focusing on the relationships between ideas and external representations, and the impact of producing multiple representations on reasoning (see Chapter 1). The findings presented support the claim that multiple external representations afford students opportunities to organize their thinking by framing elements of the problem and making explicit ideas that they must consider. Students' interactions with different representations and different ways of seeing the problem presents us, researchers and teachers, with a rich and complex portrait of their reasoning and thinking about air and compression.

The linked-syringe device containing air provided an opportunity for students to engage with compressibility, which is a fundamental property of gases. With the linked syringes, a student can press both plungers simultaneously (i.e., the “compression case”; see Figure 25) resulting in two sensations: (1) air’s resistance to compression felt through the plungers, and (2) compressed air (i.e., air re-equilibrating with the atmospheric pressure outside the device) causing the plungers to extend when released to their position in the “at rest” condition. While these sensations are obviously intimately related, students talked (as described in detail below) about two distinct observable phenomena: (1) the point at which the plungers could not be pushed in any further without causing the seals of the syringes to fail, and (2) the tendency of the plungers to move back out of the

Figure 25. The compression case, pushing both plungers simultaneously, with the air-filled linked-syringes.

syringe chambers when the forces applied by one’s hands are removed. These two situations formed the basis of students’ explorations of the syringes in each interview, and the compression case became a focal point for their reasoning about air. Further investigation of ideas about compression was stimulated when the students were given the chance to explore a similar device containing water; a device in which compression was not possible and the resistance to compression was immediately felt in the syringe plungers, which did not move when pressed. As a student said when pushing the water-filled syringes, “It feels hard.” The comparison between air and water in the syringes was intentionally chosen to direct students’ attention to the material composition of air, and to what might be different about air and water that would allow for these differences in compression. This chapter presents a collection of results from all the students in the study, in terms of verbal statements and drawings, illustrating their reasoning about compression in the linked-syringes.

Talking and Drawing Compression

The first interview session focused on students’ verbal and drawn representations of compression in the linked syringes. In this section, I will present findings to show that students predicted the compression case with reasonable accuracy (before experimenting with the actual device), offered spontaneous explanations for what they experienced once given the opportunity to explore the linked syringes, and refined their explanations as they represented their thinking both verbally and on paper.

Students’ predictions about the compression case

Students explored the pushing case in the linked syringes before they were asked to predict what would happen if both plungers were pressed at the same time. Eight of the 12 students (Isis, Nicholas, Norris, Oriana, Oscar, Perry, Sarah, Tasha) said that the plungers would not move in at all, with the most prominent explanation being that "air would get stuck" in the connecting tube. Four of the twelve students predicted that the plungers would move in when pressed, three of whom quantified the amount, and one student (Wanda) did not quantify her prediction. The three students (James, Kandice, Kendra) who quantified their original predictions, were possibly motivated by information they gathered by exploring compression in the single syringe: Kandice said, "Cause...before, when we put our finger [over] it [the syringe nozzle] we could have done it [compressed the air] *a little bit*" (quantification italicized). James and Kandice both said the plungers would move in "a little bit," and Kendra said, "...not to the top," meaning the plungers would not move all the way to the top of the syringe barrels. Students' predictions, whether predicting the plungers would not move, would move without quantification, or would move with quantification, suggest a comfort with predicting the behavior of the syringes[24] and a capacity for reasoning about air inside the syringes being compressed.

Students were able to reason specifically about air in the context of the syringes, despite having shown that their numerous ideas about air in general referred to open air environments (e.g., air is wind, we need air to breathe, air comes from trees; see Chapter 6). This may seem like a trivial point, but the literature suggests that some students of this age may not believe air exists inside closed containers (Driver et al. 1994; Séré, 1985). Yet the students in this study

[24] And possibly a comfort with predicting the outcome of investigations in general.

were able to reason about air inside the syringes even before exploring the device. The diversity of predictions about plunger movement - no movement, quantified movement, unquantified movement (i.e., Wanda) - suggests that students can reason about air in the context of the syringes, but their ideas about *what air is* are varied. Predicting that the plungers will not move could be interpreted as the students not considering compression as a possible outcome of pressing both syringe plungers (i.e., air is incompressible). For those who predicted that the syringes would move a little bit (i.e., offering quantification), one explanation for their predictions could be that air only exists in the syringe chambers (not in the connecting tube), and thus the plungers would move in until the space in the connecting tube was filled. Alternatively, their experiences exploring the single syringes (such as Kandice's case) may have informed their reasoning about compression, and this idea was applied to predicting the compression case. Finally, with the student who did not quantify her prediction of the plungers moving (Wanda), it is difficult to speculate reasons for her predicting movement without qualification. However, with all three categories of prediction, the ways students reasoned about what might happen when both plungers were pressed suggests they think about air as "something," the composition of which was not expressed or explained until they further explored compression in the linked-syringe device.

Why do the plungers stop?

Following the predictions, students explored the linked syringes and tested their hypotheses. Some of those who predicted that the syringes would move in showed faint moments of surprise. Wanda was surprised by how little the plungers moved (*Interviewer:* Is that was you expected? *Wanda*: No). She elaborated on her surprise by saying, "Well, it was hard to push it up and, like, there was still more air [in the syringes]." While she predicted the plungers would move in when pressed, something about trying it with the actual device surprised her, and that prompted her to explain her surprise by adding "there was still more air" in the syringes, as though she was surprised that air remained in the syringe barrels (as opposed to going into the connecting tube). However, overall the students who predicted some movement by the plungers were comfortable with their observations, and all students were asked to explain why the plungers reached a stopping point.

One idea that emerged was that pushing both plungers results in "too much" air to fit into the connecting tube, or there was too little space for all the air in the syringes. Students using *space* to reason about compression had the following verbal explanations for why the syringes' plungers stopped:

Isis: "All the air doesn't fit in it [the connecting tube]"; "because all the air, like, there's too many."

Kandice: "...Not enough space for all of the air"; "It's not enough space."

Norris: "The air is getting stuck right there...like in...kind of...in the middle"; "Cause there's too much air out"; "Cause two strong air is coming at the same time"; "There's already air in there [one syringe], and there's already air in here [other syringe], so, like, so if there's too much air out it probably can't go."

Oscar: "Both airs are gonna be still in the same place"; "Because it has enough air, so you can't, if you're gonna press them harder, then that's gonna maybe explode or take off."

Perry: "If you press on it, there air doesn't have no where to go."

Oriana: "Because there's air in both of them so it can't go up."

Students used phrases such as "too much," "not enough space," or "too many" to refer to the quantity of air inside the connecting tube during the compression case, as well as the amount of space inside the linked syringes. If students conceived of the air in each syringe as two distinct quantities, then an attempt to push each of these quantities into what looked like a smaller amount of space, the connecting tube, would result in the plungers stopping, as the students experienced. Explanations of this sort did not include much in the way of explanations about mechanism or explanations that linked cause (pushing the plungers) with effect (the plungers stopping) - they were descriptions of competition for space (see Tytler, 1998). In other words, quantity of air *A* added to quantity of air *B* requires a volume of space $A + B$, and for these students the connecting tube did not appear to have a volume of space totaling $A + B$.

A second idea used to reason about compression involved the *movement* of the quantities of air in each syringe. Students using movement to reason about the compression case focused on how air from each syringe moved, and where each amount of air was located when the air was being compressed, as opposed to the specific quantities of air and space. Examples of reasoning with ideas about *movement* include:

James: "It gets stuck."

Nicholas: "If you try and push both of them together, it's gonna stop right there [middle of the connecting tube]"; "It's impossible because it's stuck."

Tasha: "Because you're pushing them at the same time, and they get stuck in the long tube [connecting tube]."

Wanda: "It can't go to both sides"; "Cause if you're pushing it up like this, it won't go to both sides, and it's really hard."

Based on the different ways that students used the word "stuck," I interpret the term to have two different dimensions. First, if compression is considered as two distinct quantities of air moving out of each syringe and into the connecting tube, then "stuck" could imply a ceasing of motion - the air is no longer moving, and as such the plungers themselves are "stuck." This explanation would constitute more of a description of the behavior of the plungers than a particular description of air moving in the linked syringes. However, other students' statements focused on the connecting tube, such as Nicholas saying, "It's gonna stop right here [middle of the connecting tube]." Similarly, Tasha said when both plungers are pressed that "they [air] get stuck in the long tube [the connecting tube]." I interpret these statements to imply that "stuck" is referring to where the air moving in the linked syringes stops in the compression case. The focus on "stuck" occurring in the connecting tube (as Nicholas and Tasha explicitly pointed out) suggests that these students were talking about air from each syringe moving into the connecting tube where the air could move no further; the term "stuck," thus, signifies a lack of movement of the air in the syringes and connecting tube. Such an explanation is similar in nature to the first explanation involving space, in that the total volume of air is central. That is, the total volume of air in the syringes, if you keep pushing the plungers, eventually gets "stuck" in the connecting tube and is unable to move any further. In this sense, "stuck" could imply that air is incompressible, as the total volume remained constant. Regardless, the term "stuck" appeared to have nuanced meaning where it referred to the movement of the plungers as well as the imagined movement of quantities of air inside the syringes.

A third, and final, category of explanations involved students reasoning about *strength* to explain the compression case. Students using this explanation discussed the difference between the force applied by one's hands and air's resistance to compression. Students offered the following explanations:

Kendra: "...There's not enough strength to push it in."

Sarah: "The air's like, that one [left hand syringe] is pushing into that one [points to right hand syringe], but that one [right hand syringe] at the same time is pushing into that one [left hand syringe]. So, it's hard, to...the air is too strong. And it can't push."

Wanda: "...The air has force to keep it like that"; "The air is forcing it to like not be strong enough to push all the way up here."

Given the bodily experience of compressing the air in the syringes - the visceral reaction of the plungers transmitting the resistance of air to the applied force to one's hands - the use of strength as well as intuitive ideas about pushing to explain the compression case are natural resources for making sense of air's compressibility. However, the ambiguity of the term "strength" poses some interesting challenges for researchers analyzing student thinking, as it is unclear whether the strength in question is the applied force on the plungers (i.e., the person pushing), or the air resisting compression. With Kendra, it appears the "enough strength" she referred to is the amount of push from the plungers, imposed by one's hands. With Sarah, her statement, "The air is too strong," suggests that she was reasoning about air's resistance to compression. We would expect that a first attempt at describing a complicated phenomenon like compression would yield ambiguous use of terms like "strength," similar to the previous two descriptions of explanations for compression, where ideas of *space* and *movement* were murky and confounded at best.

For many students, verbal descriptions of complicated processes that are invisible to the naked eye are challenging. Students here demonstrated abilities to reason about air and compression, but their verbalizations were relatively vague and far from comprehensive. Further attempts to explain why the plungers move back out of the syringes when released from the compression case confirmed the challenges students faced when verbalizing their thinking.

Why do the syringes move back out when released?

Students were further asked why the plungers moved back out of the syringes once released from the compressed state. Explanations of why the plungers stopped when the air in the system was being compressed relied on ideas of *space*, *movement*, and *strength*, however, these ideas were scarce in explanations provided for the "push back" of the plungers. Only two students reasoned about space in their explanations of the push back of the plungers:

Isis: "There's too much air in the tube, so when you let go all the air bounces back to where it was before."

Oscar: "There air is like right there [in the connecting tube], so it has a certain amount [of air], so when you're going like that... [student releases plungers and they move back]."

However, the majority of students reasoned that it was the air itself, inside the syringes, that caused plungers to push back. In other words, they said the reason for the push-back of the plungers was simply that the air in the connecting tube was pushing the plungers back out of the syringes.

James:	"Both of the air is pushing both of them down."
Nicholas:	"Air is coming back to where it was"; "It can't go any further...of course it will have to go back to where it was."
Norris:	"Probably the air is probably pushing it back down."
Perry:	"Cause all the air was in here [connecting tube], and then some of the air went in here [one syringe], and some of the air went in here [opposite syringe]."
Sarah:	"When you let go, um, the air is, um, if...it's, it's weak now and it comes...right back out."
Wanda:	"...Because of the air inside [the connecting tube]."
Oriana:	"The air is pushing both of them down"; "Since a force is not pushing the air one way, it's just pushing both of them down."
Tasha:	"Because some of the air inside the tube is gonna come back down into the tube and some of the plunger is gonna go back down."

The students' explanations included ideas about air pushing on the plungers, and ideas about a possible "normal" or "default" state (e.g., "Of course it will have to go back to where it was"; "Since a force is not pushing the air one way, it's just pushing both of them down"). While their explanations offered ideas about cause (e.g., “Since a force is not pushing the air one way”) and effect (e.g., “The plunger is gonna go back down”), the students did not offer descriptions of possible linking processes at this point in the interviews. The majority of students (10 out of 12) focused their reasoning on descriptions of the behavior observed in the compression case (plungers moving in, stopping, and moving back out again), without explicitly addressing a mechanism (i.e., linking process) that would account for compression. However, a few students began exploring reasons for what they observed:

> *Nicholas*: “...Kind of squishy”; “like, no room”; “I went in this car with my cousin. But, it’s too squished together and we can’t go any further until we get out the car.”
>
> *Oscar*: “It’s [the air] getting pressured”; “Oh yeah, like in doctors. You know how they put that thing [blood pressure cuff] around you and then go pssst pssst pssst?”

Nicholas and Oscar recalled experiences - being “squished together” in the back of a car, or the feeling of a blood pressure cuff “getting pressured” - that helped them begin to elaborate on their explanations of compression. The examples they volunteered related to the experience of pressure (e.g., feeling the plungers stop moving), which could be interpreted as a step toward developing a description of a process linking cause and effect. However, at this time their descriptions did not include specific mechanisms to explain the “pressure” to which they referred.

Attempts to explain the two experiences with the syringes - the plungers stopping, and the plungers being pushed back by compressed air - created different opportunities for students to reason about compression. On the one hand, students were comfortable explaining why air from each syringe moving into a smaller connecting tube was met with resistance (as evidenced by the plungers stopping). They used their intuitive ideas about *space*, *movement*, and *strength* to generate an explanation of this particular case. On the other hand, students relied on different ideas to explain the "push back," primarily including descriptions of the process of compressing the air and almost teleological explanations of air as the causal agent. A particular mechanism or linking process between cause and effect - for example, the volume of air decreased causing the pressure to increase, which results in the plungers moving back out when released - did not appear readily available to these students. Within one context - compression in the linked syringes - students must construct and refine their intuitive ideas to articulate explanations that encompass more phenomena. That is, reasoning about space, movement, and strength to describe compression in one direction (i.e., pushing in of the syringes) must eventually be adapted to describe the inverse effect of compression (i.e., push back of the syringes). Refining one's reasoning involves building from initial ideas, which can be facilitated by the introduction of new ways of representing the problem; this is a claim supported by evidence from the students' drawings I present below.

Students' initial verbalizations about compression suggest they rely on certain lines of reasoning to explain what they experienced (space, movement, and strength), and their descriptions of what happens when pressing both plungers at the same time likely precede attempts to explain possible mechanisms for what they observe. If we consider more carefully the reasoning underlying the students' explanations, the particular variables under consideration - space (i.e., volume), movement, and strength (i.e., balance of forces) - are essential elements of how a scientist might explain air being compressed. Granted, the ways in which students talked about space, movement (of gross quantities of air), and strength (being an internal quality of air) are non-normative. However, collectively their initial explanations included critical features of compression in the linked syringes; each explanation being a unique application of one or more of these critical features. The identification of critical features (volume, movement, forces) on which to focus provided students with a foundation from which to explore their thinking further using a different medium - pen and paper.

How could you show on paper what happens when we press both plungers at the same time?

The theoretical framework for this dissertation highlights the role of external representations in organizing thinking and highlighting specific aspects of ideas for reasoning and reflection. Just as humans' attempts to put the world on paper changed the structure of knowledge in many ways (Olson, 1994), students' attempts to represent air in the syringes on paper influenced their reasoning about compression. Before the introduction of the drawing task, the majority of students reasoned with one of three ideas - space, movement, and strength - when explaining why air can be compressed. While some students blended ideas in their explanations (Norris, Nicholas, Oscar), most students relied on a single variable or feature to explain compression. However, during the drawing session, more students began to broaden the scope of their explanations to include combinations and permutations of these three central ideas; I will present evidence suggesting students are able to generate increasingly detailed and multifaceted explanations of compression when given the opportunity to represent their thinking on paper.

In the early exchanges of the first interview, students described the air with phrases like "both airs" (Oscar) and "two strong air(s) coming at the same time" (Norris), which suggests a model of the syringes with two distinct quantities of air - one in each syringe. With this model, when the plungers are pressed simultaneously, "both the air" (James) - one quantity from each syringe - are pushed into the connecting tube. The momentary model (developed in the context of the linked syringes) of two quantities moving out of the syringes and combining to fit into a smaller space (i.e., the connecting tube) helps to explain two descriptions offered by the students.[25] Students used ideas of space (i.e., the amount of air relative to the space in the tube; "too much") as well as ideas about movement and the discontinuation of movement ("air gets stuck") to help explain

[25] I acknowledge that it remains unknown whether the two-quantity model fueled the verbal explanations, or whether attempts to explain lead students to articulate the model. It is plausible that the model and representation (i.e., verbal utterance) are co-constructed, which is more aligned with a dynamic resources-based perspective of students' reasoning; this is an area that deserves significant future research.

why the plungers stopped moving. This momentary model, developed orally, was captured in students' drawn representations as well, which the evidence presented below reveals.

Nine of the twelve participants chose to draw the pushing case in their first production. One possible explanation for this trend was that the challenge of explaining compression led students to focus on the pushing case first, as describing how air pushes on something may be a more accessible idea.[26] Regardless, all students were asked to show compression (those who spontaneously drew compression, and those who did not), and many of the students included elements in their drawings suggestive of the two-quantity

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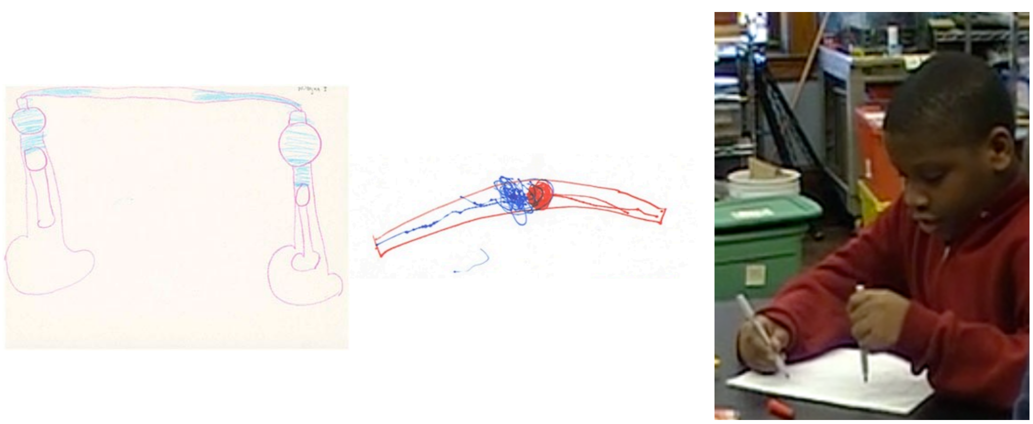

Figure 26. (A) Wanda's drawing of compression, (B) Perry's drawing of compression, (C) Perry using two different markers to draw compression (Figure 26.B).

model. For example, Wanda (see Figure 26.A) drew two syringes and she shaded the inside of them along with part of the connecting tube, leaving the midpoint

[26] Alternatively, since the students were asked to explore the pushing case first, they may have felt obligated to generate a drawing of that case before drawing compression.

unshaded. Perry (see Figure 26.B) made a similar move when elaborating on the idea of "air gets stuck." He drew a section of tube and selected two pens to draw each quantity of air in a different color (see Figure 26.C). As he drew, he said,

> ...the air, both of the airs, both of the airs go like this, and they all get stuck right here [middle of the connecting tube] cause they have no where to go, cause that one [air shown in blue] wants to go in there [middle of the connecting tube] but that one [air shown in red] want to go in there [middle of connecting tube] too, so they're all forced together like a big wall.

Perry used two different colored pens, each held with a different hand to highlight even further the distinction between two quantities of air. He used deliberate language to identify each quantity of air coming from each syringe and a description of a "big wall" to talk about his ideas about compression. Perry's idea involved two amounts of air coming together in the connecting tube where the two quantities of air are "all forced together." Including Wanda and Perry, seven of the twelve students drew the compression case in a manner suggestive of the two-quantity model, in which they used lines, line segments, or dots moving out of each syringe and meeting in the middle of the syringes. The focus on the midpoint of the connecting tubes was not only captured in their verbal descriptions, but also with a number of different symbols employed by the students to highlight the significance of that midpoint (see Figure 27). Students used arrows (Figure 27.D, 27.E), words (E, F), lines (A, C, F), line segments (E), gaps in line segments (B, D, F), and scribbles (A, C) to call attention to the middle of the connecting tube. I contend that these symbols were used to represent phenomena students believed to be occurring at the midpoint of the tube. They may not have initially had a particular way of describing what was happening at this point, but their symbols and inscriptions denoted the importance of that location in the linked syringes. Students obviously could not see what was

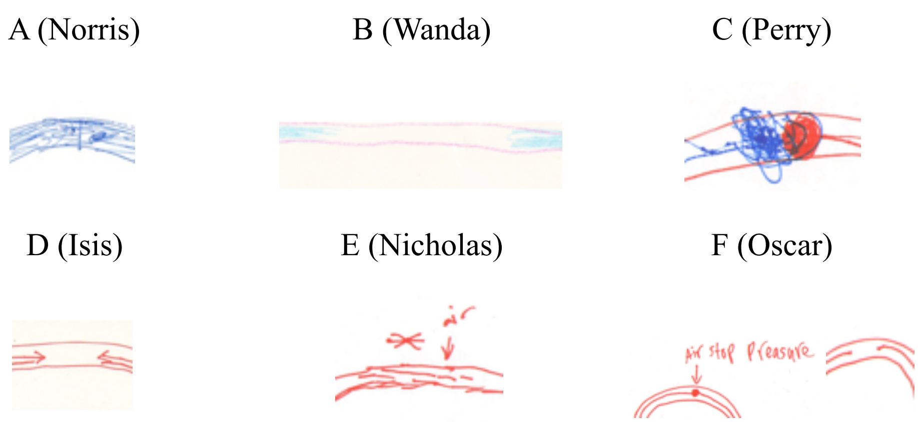

Figure 27. Symbols used to indicate the importance of the midpoint of the connecting tube in the compression case.

happening in the syringes, but their production of an external representation of that phenomenon served to organize their thinking about compression by finding points in the system on which to focus.[27]

Brizuela (2004) reports on young children's attempts to appropriate conventional written numbers, which she claims is not automatic. Children experiment and explore systems of representation as they construct and adopt particular conventions. For example, Brizuela featured the story of George, a 5-

[27] See Appendix D for a chart of all students' representations of compression, their utterances explaining their productions in the various forms, and the symbols they used for air. Appendix C lists the general numeric trends (e.g., X of 12 students) listed throughout this chapter.

year old, attempting to represent “teen” numbers (e.g., 13, 14, 15) on paper. George was unaware of the convention of placing a 1 before the second digit to generate the written version of a “teen” number (e.g., placing a 1 in front of 7 becomes 17, or “seventeen”). While he could count easily using teens, he was uncertain about how to represent these numbers in written form; he used zeroes to represent the teen (i.e., the 1 in the tens place), in addition to representing the number which he knew how to write, the 7 (e.g., 17 was written as 70, with the zero standing for “teen”). Brizuela relates George’s inventive use of zero to a body of literature on children’s use of dummy letters and numbers (Alvarado & Ferreiro, 2000; Quinteros, 1997). Dummy numbers and letters are symbols used by students to represent an element of a number or word that the student knows should be included, but at the same time does not yet know which particular element needs to be included. Thus, students generate inscriptions to highlight some idea or to demonstrate differences as they begin to construct conventional means for representing written numbers and letters.

With students in this study, the symbols they included at the midpoint of the connecting tube of the syringes appeared to serve a similar role to the dummy number about which Brizuela (2004) writes. The symbols (see Figure 27) are means for the student to explicitly represent a point they know is important in describing compression. They may not yet know how to describe what is happening at that point. Nor do they have specific ways of describing a mechanism relating that point to explanations for the plungers stopping or moving back out when released because of air's resistance to compression. Yet, they are capturing an element of their thinking through the representation that they know deserves attention. In a way, they seem to be stating, "I know something important is going on right here in the middle of this tube, because I experienced with my own hands what was happening. I don't know how to explain it, or why it happened, but I will mark it, so I can keep thinking about it and so you [the interviewer] know that something is going on there." While there are no conventional ways to depict compression on paper, the invented use of symbols as signifiers of importance mirrors children's use of dummy numbers and letters in other contexts. In turn, the external symbols denoting activity at the midpoint of the connecting tube supported students' efforts to refine their verbal explanations about compression.

"Explain your drawing to me"

The inscriptions students created offered them a focal point for their reasoning and a means for organizing their conceptual resources (diSessa, 2004) for making sense of compression. As students completed their drawings, they were asked to verbally explain what they drew. Oscar began explaining the particular inscriptions in his drawing (see Figure 28.A) by saying:

> ...you can see that I labeled 'air stop' because of pressure...pressure. Because I put the ball of pressure [I assume he means the dot he drew in the middle of the connecting tube], like, people don't know, like, you

> don't, like, you know that if you do the same thing it's gonna be in the middle. So, then I just put the ball [i.e., the dot in the drawing] to say that both airs are just going to go like ssssshhhhhh together.

In Oscar's drawing, he explicitly labeled the midpoint of the connecting tube (see Figure 28.A), adding written labels and a dot, which he called the "ball of pressure." In his description of what he drew, Oscar talked more specifically about two distinct quantities of air coming from each of the syringes to a point where they go "together" in the middle. His drawing includes a representation of some event, which he called "pressure,"[28] in the tube. The drawing also illustrates his desire to make the drawing decipherable by some hypothetical audience for the drawing ("people don't know"). Motivated either by a willingness to communicate his understanding or to make sense of compression himself (or both), he added specific elements to his drawing to direct the viewers' attention to whatever that event was in the middle of the tube. Oscar was asked to elaborate on the idea of "pressure," and he generated a second drawing (see Figure 28.B) to show his thinking. He described this second drawing by saying, "...you know the pressure is, um, together. Um, I just put a little gap to say that the air's just going like ssssshhhhh, so if...let's see...how would you say it?" Oscar had trouble

[28] Which may be related to the sensation of pressing both plungers at the same time, which reminded him of a blood pressure cuff: "Oh yeah, like in doctors. You know how they put that thing [blood pressure cuff] around you and then go pssst pssst pssst?".

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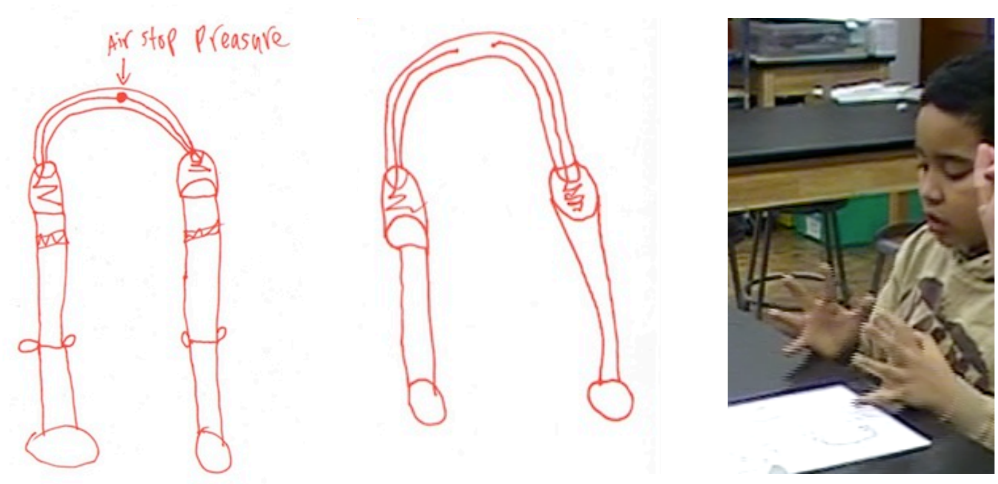

Figure 28. Oscar's drawings of compression, and gesture explaining the "gap." (A) His first drawing with the label "air stop preasure [pressure]" and a dot; (B) his second drawing showing the "gap"; and (C) Oscar's gesture used to explain the "gap" he drew on paper (see Figure 28.B).

articulating his ideas verbally, and he grabbed the linked syringe device to explore the compression case again, acting out his thinking in an attempt to articulate his reasoning. As he manipulated the syringes, he said:

> If you go like that [compression], you can't see nothing [i.e., you can't see what is going on]. But you know that there's gonna be a gap, because one of that [a syringe] is going that way, the other one [the second syringe] is going that way. So then that air [air in one syringe] is gonna go like that [motions with the marker to show air moving from one syringe into the middle of the tube], but then that...if you push them both, then it's [both quantities of air] gonna go right there [the midpoint of the tube] and then you're gonna see a big gap because it just goes like that [makes gesture with hands demonstrating "gap" - see Figure 28.C].

Oscar left a blank space in between the lines representing air coming from both syringes[29] "to say that the air's just going like sssshhhhh," the air is meeting in the middle of the tube where pressure and resistance occurs. His deliberate use of symbols (e.g., labels, a dot, the "gap") to call attention to the elements of his reasoning (e.g., air meeting in the middle, the "pressure") demonstrates the interrelations between what he put on paper and how he reasoned about air. Before drawing was introduced, Oscar's reasoning was a bit scattered and incoherent, as is evidenced by his first description of the plungers moving out of the syringes when released from compression:

> I think because when...if the air...like I told you, the air's like right there [middle of tube], so it had like a certain amount, so when you're going like that...wait, like that [compression case], the air is gonna go like that [plungers push back out] and the air is gonna be, it's gonna, it's harder.

While his explanation contained interesting elements (e.g., "a certain amount"; "it's [the air] harder"), overall his explanations lacked precision and coherence. Putting ideas on paper supported Oscar's attempts to verbalize his thinking, and as such allowed him to begin reasoning about what could be occurring inside the syringes that would result in the behavior observed with his eyes and felt in his hands. Oscar stated that, "You can't see nothing...but you know there's gonna be a gap." I interpret this to mean he was aware that his representation was, as Enyedy (2005) suggests, "Highlighting aspects of [his] experience and communicating

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[29] This is the same symbol Isis, Wanda, and James used to highlight the midpoint of the tube in their drawings.

them to others and [himself]" (p. 427). Reaching a level of comfort generating external symbols that stand for (or correspond to) things one cannot see is a substantial achievement; constructing an explanation alongside the production of a representation fuels students' reasoning about that which they cannot see. The act of generating a representation highlights some aspect of the particular situation that communicates that idea to others, as well as making it more salient for ourselves (Enyedy, 2005). With the case of compression, the drawings that students generated and their various symbols for what was occurring at the midpoint of the connecting tube elevated their explanations by allowing them to reason about specific elements of the system, as was evidenced by Oscar. By organizing their thinking and making explicit aspects of compression, students were able to generate more coherent explanations, which tended to involve combinations of ideas about space, movement, strength, as shown below.

Developing explanations and more complex reasoning

The students' first attempts to explain compression verbally, particularly why the plungers stopped, resulted in utterances that tended to focus on one element of the system - space, movement, or strength. Some students offered composite explanations, involving more than one variable, but the majority resorted to unidimensional reasoning.[30] By unidimensional, I mean students'

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[30] It is important to note that while most students tended to use one particular variable or idea in their verbal explanations of compression, the features identified (space, movement, strength) are not necessarily mutually exclusive. Students may have used different variables at different times, but their explanations tended to be unidimensional and did not combine more than one idea before the drawing portion of the first interview.

utterances tended to focus on a single explanatory element, such as the plungers stop because they get “stuck,” where “stuck” comprises the entirety of the explanation for the event. Similarly, explanations of the air’s resistance to compression tended to be simplistic and lacked specificity (i.e., air made the plungers move back out). However, after completing the drawings, students were asked to explain how their drawings showed compression. In doing so, they began to blend aspects of compression to generate composite explanations, involving more than one of the three elements of the system they had referred to earlier, prior to drawing. Nicholas began describing his drawing of compression (see Figure 29) by saying:

> Well, this is the tube...so, the tubes [writes the label “tube” - meaning syringes], and this [small red line segments] is the air. And what happened is the air is pushing together, so that’s what this [inscription at the midpoint of the tube] means.

Nicholas made two inscriptions in his drawing that called attention to the middle of the tube and to two quantities of air. The first was the use of small line segments that were only located at the midpoint of the connecting tube.[31] He labeled these line segments with the word “air.” In addition to these representations of air, he drew two arrows facing each other above the midpoint of the connecting tube (see Figure 29). The arrows facing each other were

[31] Between the syringes, not the “tubes” he referred to in his drawing, which are the syringes.

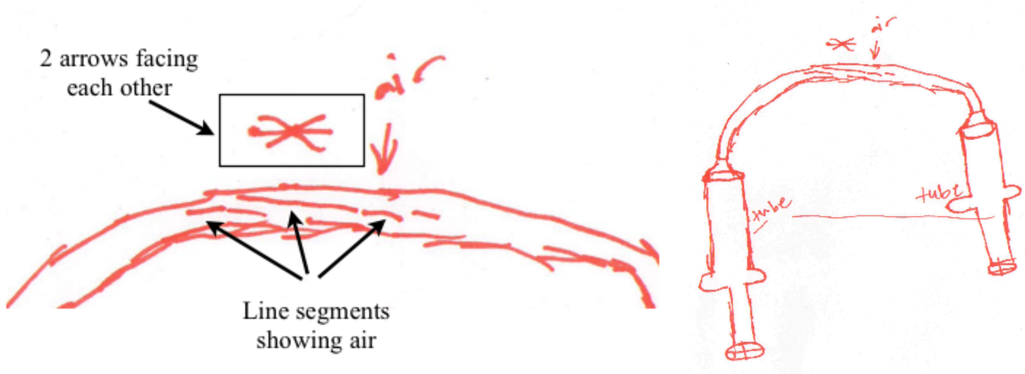

Figure 29. Nicholas drawing of compression: symbols for air and compression (left), and the overall drawing showing the syringes (right).

described as, “What’s also happening is that the air, it can’t go any farther, so it’s staying here. And...what happened is that all the way at the top. See? Right here [points to arrows in drawing]?” Nicholas described the air as “pushing together,” which, when considered alongside the two arrows drawn facing each other, I interpret to mean there are two quantities of air “pushing together” in the middle of the connecting tube. He adds that the air “can’t go any farther,” because “the air is going all the way right here [middle of tube], and this air is going all the way right here [middle of tube], and they’re getting stuck.” As he described this using his drawing, he pointed specifically at air coming from each of the syringes independently. Nicholas reasoning involves a combination of the movement of air from the syringes into the connecting tube where they get “stuck,” and the notion of two distinct quantities of air contained within the syringes. Before the drawing session, Nicholas described this scenario by saying, “If you try and push both of them, it’s just gonna stop right here [points to the middle of the tube].” His reasoning focused primarily on movement of air inside the syringes, and where the quantities of air would stop. Yet, his drawing and his explanations of it included ideas about the amount of air (i.e., reasoning about space) moving in the syringes. Nicholas drawing, and specifically his inscriptions at the midpoint of the tube, focused his reasoning on what might be happening in the connecting tube; he was able to combine ideas of space and the movement of those amounts of air to refine his thinking (albeit, still very much intuitive ideas about air in the syringes). Oriana, another student, provided similar explanations where she elaborated on notions of "stuck" while describing her drawing without highlighting the midpoint explicitly.

Norris was one of the few students who offered multidimensional explanations in the first portion of the interview, reasoning about space ("too much air out") as well as movement ("they get stuck"). These two ideas were used relatively independently, as opposed to combining them into one coherent explanation. In the drawing session, Norris combined quantity and movement into a single explanation when he said:

> They get pushed out [of one syringe into the connecting tube] and it's crowded in here [in the connecting tube]. And then they get pushed out at the same time, but it's crowded in here [in the connecting tube]. They won't have a place to go, cause it's filled, and they won't have a place to go cause this [the connecting tube] is filled.

Norris said this as he drew repeated circular scribbles (see Figure 30) increasing in concentration to illustrate his notion of "crowded." Norris' combination of air

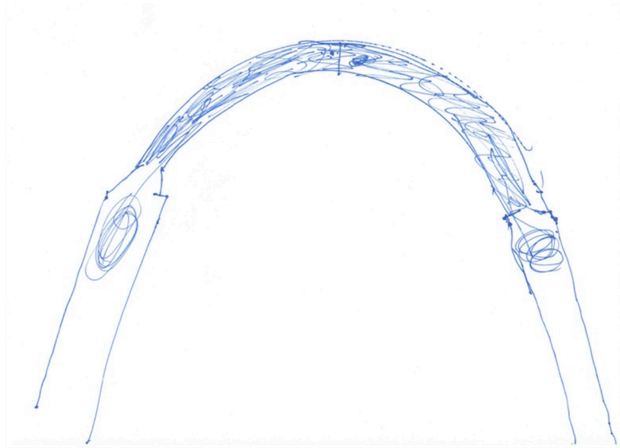

Figure 30. Norris' drawing of compression (with line at midpoint indicating the importance of that point in explaining compression).

moving from each syringe into the connecting tube with the idea of "stuck" from his earlier statements resulted in his use of "crowded" (he used "crowded" in the context of "people," imagining the lines to be people moving in the syringes, see Chapter 6) that comprised a composite explanation. The story he now told about compression combined different ideas and was slightly more coherent than his first attempts. Through the drawing, he developed a more detailed and descriptive verbal explanation of compression by introducing the idea of "crowded" to explain how air might be compressed in the syringes (an idea that later catalyzed his animation further articulating a mechanism to help explain compression).

As the vignettes of Nicholas and Norris illustrate, the process of generating a drawn representation of the syringes led students to articulate further their initial ideas about compression. Generating symbols that signified the importance of the midpoint of the connecting tube placed ideas about compression into the external world for reflection and evaluation. Students directed their attention and reasoning to what might be happening at this point to explain compression in the syringes in greater detail. Attempts to explain their drawn representations resulted in students combining some of ideas that were expressed in the oral language portion of the interview to offer more specific and sophisticated explanations of compression (e.g., Norris' explanation of "crowded" as the result of reasoning with movement and space). In other words, students expressed and reasoned with a seemingly fragmented set of ideas before drawing was introduced, and the process of representing their thinking on paper allowed them to begin creating relationships between these fragmented ideas to generate more complex, composite explanations. The relationships constitute the substance of the students' reasoning; as students wrestle with explaining what they observe, the ways they use and combine ideas are the fuel for their future attempts to refine understanding.

Ultimately, the increased specificity of the students' verbal descriptions led some students to begin generating composite explanations of compression, which combined variables like space, movement, and strength. While these explanations began to address causal patterns, possible processes that link cause and effect were minimally articulated in this session (with the exception of Isis - see Chapter 4). However, with increased attention to elements of air in the syringes, students were primed to begin suggesting and developing particular mechanisms that would explain compression (or at least begin to think about causal patterns); a process that began in the subsequent session involving the production of stop-motion animations.

Expanding reasoning to the syringes filled with water

The inability to make the plungers move in the water-filled case surprised a number of students, and the most common explanations were that water had "more strength" or "more force" than the air. When asked to clarify their thinking, students were forced to compare the composition of these two substances, which lead many of them to declare that air "isn't really anything." For example, Kandice said, "Air is sort of like nothing." Oriana said, "Water is, like, a actual thing and air is like...I think that water just has more force." While students claimed that "air is nothing," I interpreted these utterances, specifically "air is nothing," as a token use of a familiar phrase (the literature suggests that students at this age do not believe air has weight or is even a material substance, see Driver et al., 1994; Stavy, 1988). Oriana's statement is indicative of the challenge students faced after they had talked about air in the syringes, drawn air on paper, and experienced compression. Their attempts to explain compression used implicit ideas of air being a substance, which conflicted with their, perhaps more habitual, statement that air is "nothing." When comparing the two substances, the statement that air "is sort of like nothing" is a comfortable descriptor of air relative to water. Yet, without an alternative description of air that could explain the differences in compression between water and air, this idea of air being “nothing” remained robust and prominent. Some students were able to reason about the material composition of air, but ideas about what air is remained scarce during this first interview.

Animating Compression

The second interview session involved students generating a dynamic representation of the syringes, in stop-motion animation form, including explanations of the compression case. This was, for many of the students, their first attempt at creating an animation. However, animation is in essence a collection of drawings and, thus, they could use their accomplishments of the previous session to begin this representational endeavor. In this section, I present findings that reveal how animations afford students opportunities to re-represent their ideas; refining, amending, or adopting new symbols for air allowed students in this study to reason about compression from different perspectives. Additionally, the results presented here highlight a unique feature of stop-motion animation. The frame-by-frame depictions of a phenomenon like compression require parsing the process into small changes where the larger observable behaviors (e.g., pushing the plungers until they stop) are captured by the accumulation of small changes from frame to frame. Attending specifically to small changes in a linear order can support students’ reasoning about processes like compression, and this section explores evidence from the study in support of this claim.

Refining representations of air as a substance

Given the sequence of the interviews, with the animation session occurring after the drawing session, students were afforded the opportunity for re-representation; generating a drawing for the animation allowed them to reflect on their initial representations, produced during the drawing session, and to reconsider how to represent air and compression. For example, Isis declared early in the second interview, before she began making her animation, “Well...I used lines [in the drawing session], but the other kids [in the example drawings showed during the drawing session] used dots...maybe I’ll use dots.” In the previous session, the example drawing showing air as dots intrigued her, and she was able

A B C

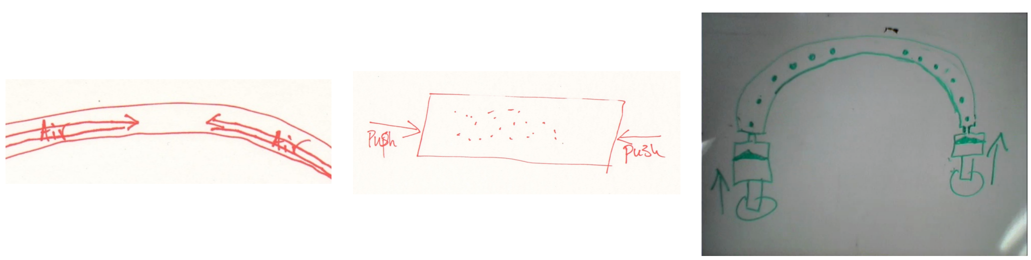

Figure 31. Isis’ symbols for air: (A) first symbol used during the drawing session, using lines to show air; (B) using dots to show compressed air during the drawing session; (C) dots used to show air in the syringes in her animation.

to talk about molecules (see Chapter 4). Her final drawing included dots as a means for describing the difference between compressed and ambient air (see Figure 31.B), but then, the dots symbol was not integrated into a representation of linked syringes (which may be inconsequential).

Given the opportunity to re-describe air in the syringes during the animation session, Isis opted to adopt a new symbol for air (i.e., using dots instead of lines, see Figure 31.C) in the context of the syringes. Overall, 8 of the 12 students in the study either revised the symbol they had used for air during the drawing session, or chose a completely different symbol (see Figure 32). An

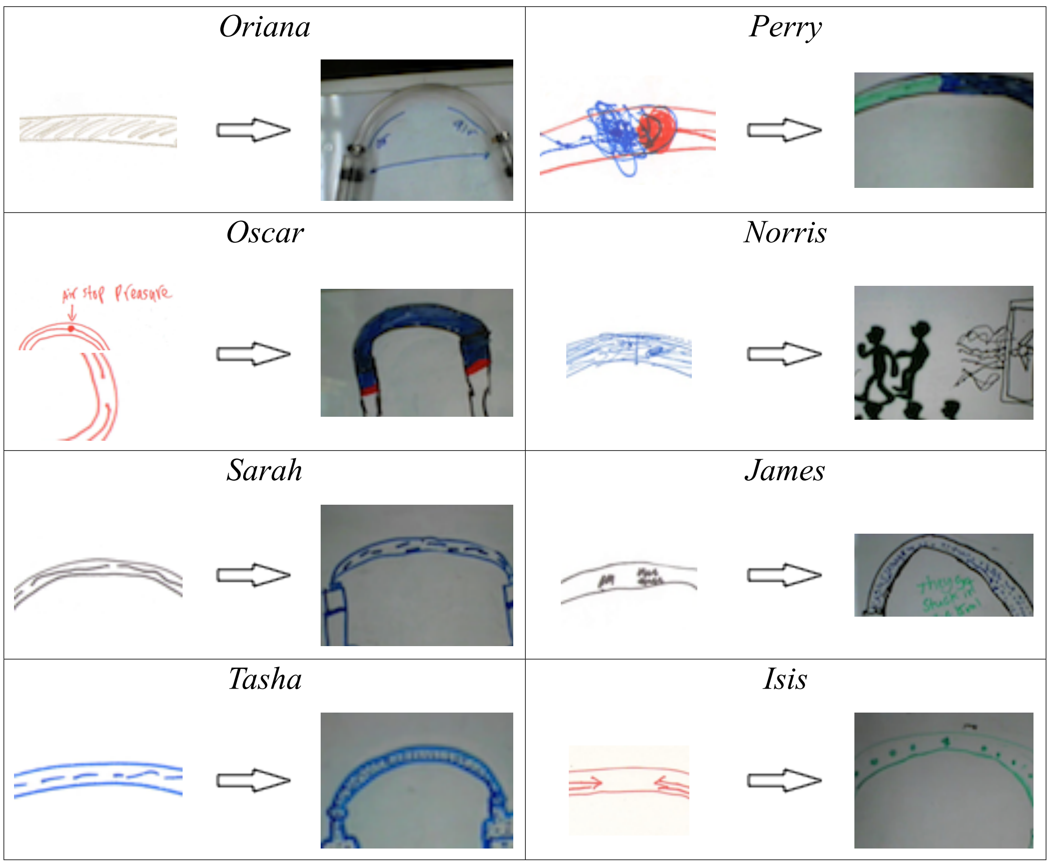

Figure 32. Shifts in symbols for air and compression from drawing to animation among the study participants.

opportunity to reconsider how air is captured on paper provided students with a chance to reason about air and compression through a different lens created by whatever newly adopted (or refined) and appropriated symbol they employed. Oscar had used thin lines to represent air (see Figure 27) in the drawing session, and shifted to using shading as means for showing compressed air in his animation. The first frame of Oscar's animation (see Figure 33) showed the syringes "just hanging out," as he said, where neither of the plungers were being pushed. In this first frame, as well as the second frame, Oscar did not use a particular symbol or shading to show air (the space in the tubes remained unshaded). However, when he described the third frame of the animation as "when they just get pressured," he added blue shading above the plungers to show the "pressured" air. After watching his movie once, he opted to add shading to the

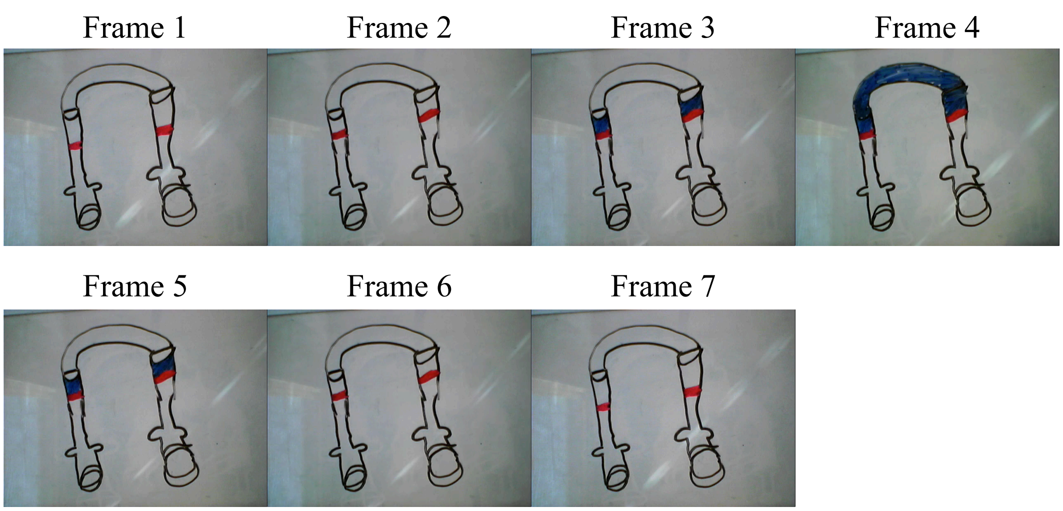

Figure 33. Frames from Oscar's animation showing shading as means for representing "pressured" air in the syringes (red markings indicate the syringe stoppers, at the end of each plunger).

entire space inside the connecting tubes (see Frame 4 in Figure 33). Oscar explained this decision:

Oscar: The reader, it's just like the reader [person viewing the animation], he wants to know, like, Okay...I see that the air is inside there, but how is that happening? Is there no...is there no air inside the tube? So I, then I just wrote the blue [shading with marker] to say that the air's just going like that [makes a gesture, see Figure 34].

Interviewer: Okay. So, it's coming together in the middle.

Oscar: Yup.

Interviewer: So, when you drew it blue like that [Frame 4 in Figure 5.10], is that showing it all pressured like you said [clarifying earlier statement]?

Oscar: Yup, it's all pressured.

Interviewer: When we're not pressing, would it look blue like that or would it look different?

Oscar: It would look different.

Oscar used the blue shading to represent his understanding of air coming from both syringes into the connecting tube where they get “squished,” or “pressured.” His use of shading throughout the connecting tube appeared to be motivated by a communicative goal (marked by his references to the “reader”), but also by an attempt to illustrate what he meant by “pressured.” Appropriating a new symbol

Figure 34. Oscar’s gesture showing how air comes into the connecting tube when compressed.

for air allowed Oscar to elaborate on his reasoning about compression, by showing the difference between “pressured” and air that is “just hanging out” in the syringes. His depiction of air “just hanging out” in the first frames of the animation did not include shading, and thus this new symbol afforded him the means for a comparison between compressed and ambient air. Additionally, Oscar’s symbol use does not appear to have been pre-planned, rather he seemed to formulate this way of showing the difference between ambient and compressed air *while* generating the animation. His adaptiveness and flexibility with this new symbol (i.e., shading) was further evidenced by his reasoning about the air’s resistance to compression.

Oscar described the why the plungers move back out when released from compression by saying, “When you let go, the pressure is just pushing that thing, the...stoppers.” To show this in his animation, he reversed the sequence of frames to depict the process of the “pressured” air pushing back on the plungers; where the blue shading disappeared from the connecting tube, then from the top of the syringes, and ultimately he removed all the shading (see Figure 33). Oscar’s understanding of compressed air as “pressured,” and his ability to represent this particular state of the gas with a new symbol (shading his animation blue instead of using lines like he did in the drawings session) further supported his reasoning.

Other students adopted discrete symbols for air during the animation session, such as dots or short line segments, to further illustrate ideas about compression. These new symbols allowed the students to show differences in the concentration of air ("there is more air") by including a higher frequency of the symbol in certain situations (see Figure 35).

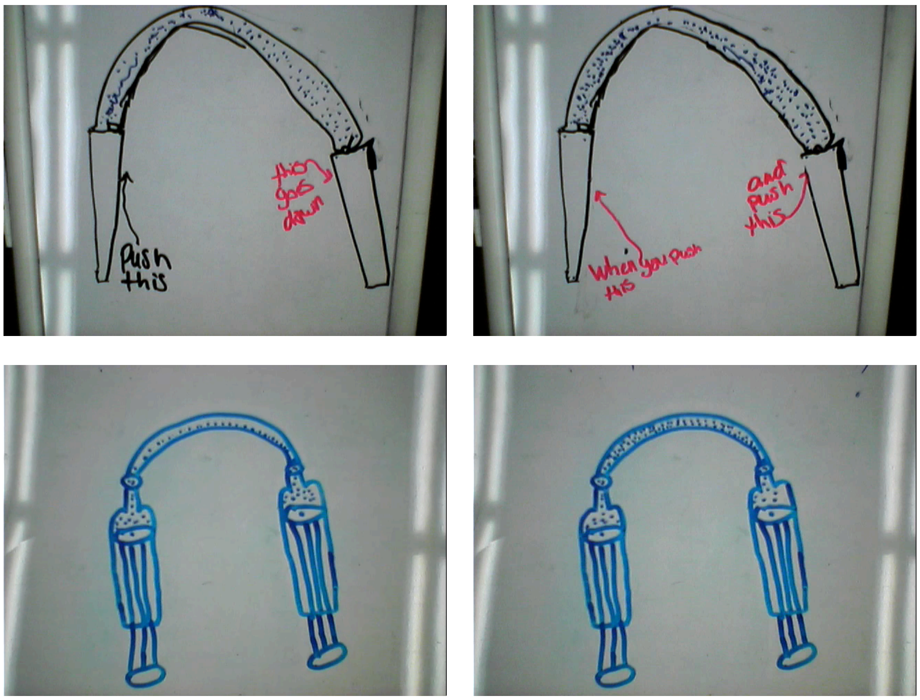

Figure 35. Frames from James' (top) and Tasha's (bottom) animations showing a higher concentration of dots (right) to depict compression in the linked syringes, compared with the "uncompressed" state (left).

Tasha, Isis, and James went as far as to reason about their discrete representations (all "dots") as "molecules," despite saying that molecules were either "in air," or simply "showing air" (i.e., they were not talking about molecules *of* air, see Johnson, 1998a). Re-representing air on paper (or on a white board) afforded students the opportunity to explore alternative symbols and ways of representing the difference between compressed and ambient air. By combining evolving ideas about compression and adaptive use of symbols, the process of generating an animation supported students' efforts to begin reasoning about mechanisms that explained compression in the syringes.

Reasoning about compression with animation

Communicating one's reasoning about compression involves generating ways of verbalizing and representing a model of how air moves in the linked-syringe system. In the oral language and drawing sessions, a general trend in the models put forth by the participants was that of a two-quantity model - where air from each syringe operates independently (see Appendices C and D). Yet, some students were challenged by attempts to verbally articulate their ideas about compression in the first session, and in the beginning of the animation session. The construction of a frame-by-frame animation provided students with a chance to reason more carefully about aspects of the syringes, and it provided an opportunity to articulate a general explanatory model for compression.[32] Stop-motion animation (as described in Chapter 3) is a depiction of some large-scale change process broken down into smaller changes per unit time (i.e., individual frames of the animation). Animation also requires the students to consider the accumulation of these small changes to describe larger, more observable

[32] I choose the term "model" as opposed to mechanism, to encompass both the ways students represented and talked about air as a substance, and the particular mechanisms that explained the observed phenomena. Some of the ways in which students explained compression did not involve particular mechanisms but instead focused on descriptions of how air may be moving in the system. Given the unseen nature of air, generating a model that describes how air may be moving in the system is a step toward generating a more explanatory, coherent mechanism that would describe compression. Additionally, I use the term "model" in a momentary sense, that is, students' models were created in particular contexts with no reason to believe this model could be applied outside of the context, as ideas of "transfer" may suggest (see Hammer et al., 2005).

processes (e.g., compression of air in the syringes causing the plungers to stop at a certain point). The opportunity to reflect on ideas about compression in a stepwise manner, facilitated by the animation medium, allowed students to more clearly articulate their model of how air moved through the syringes. In turn, students' reasoning progressed towards the explanation of possible mechanisms to describe air's compressibility; this claim is supported by evidence from the following vignette of Nicholas' efforts to construct an animation.

In the drawing session, Nicholas first focused on compression before considering the pushing case. However, in the animation session he began by showing the pushing case instead, using three small lines to represent air. The animation depicted a syringe plunger moving upward, pushing air out of one syringe and into the connecting tube while the opposing syringe plunger extended (see Figure 36). As he created his animation, he deliberately monitored what changed from frame to frame, and he utilized the onion-skinning feature within the software to assure that the motions in his animation were relatively smooth. Nicholas commented that he had done something similar to animation at home (referencing a cartoon creation website), and was thus familiar with the idea of a frame-by-frame representation. Interestingly, in the first frames of this animation, Nicholas did not show the air moving from one syringe to the other - traversing the entire length of the connecting tube - but rather he showed air from one syringe being pushed out and traversing into the connecting tube where it stopped just over mid-way along the tube (see Frame 4 in Figure 36).

Frame 1 Frame 2 Frame 3 Frame 4

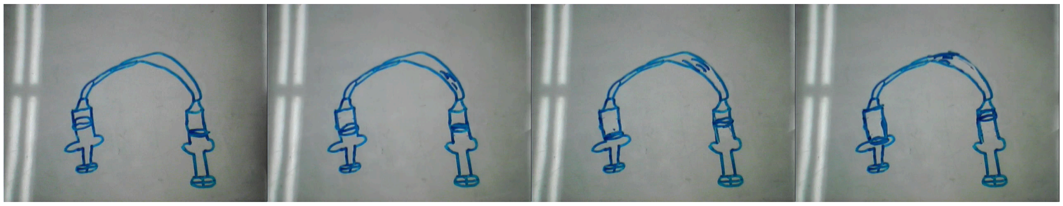

Figure 36. Nicholas' animation (Frames 1 - 4) showing the pushing case with lines representing air moving from one syringe into the connecting tube.

Concurrently, as his lines showing air moved out of one syringe, the plunger on the opposite syringe extended as though it was being pushed, just like with the syringes. Many of the students said that air traveled from one syringe to the other syringe, essentially ignoring the role of air in the connecting tube as the substance translating the force to the opposite syringe. In other words, rather than describe the pushing case as air from one syringe pushing on air in the tube, which pushed on air in the other syringe, which pushed on the opposite plunger, many students said that the air from one syringe was in contact with the plunger on the other side.[33] Nicholas' animation suggests he had some understanding of how air may be able to transmit forces. He said there was air in the whole system (syringes and connecting tube) at all times, and his animation reflected that line of reasoning; air occupying the entire space within the syringes contradicts the two-quantity model that he used to described compression, which is discussed below.

Nicholas was asked to consider how he might show the compression case, and he generated three frames (see Figure 37) showing air (using three lines

[33] This is an idea consistent with a two-quantity model, where each syringe holds a quantity of air that is passed back and forth through the connecting tube.

again) moving out of each of the syringes and into the connecting tube; he was asked to describe his animation, frame by frame.

Nicholas: Well this one [Frame 5 in Figure 37], it's where you're both pushing, both of these [the plungers] up. And then what happens is that, they [the air] end up, like, they already had air in 'em, so the air is coming all the way to the middle [of the connecting tube].

Interviewer: To the middle, like right here? In the middle of the tube [connecting tube]?

Nicholas: Yeah.

Interviewer: So, this next one [Frame 6 in Figure 37]...

Nicholas: Is about, like...

Interviewer: Okay. So, now we've started to push?

Nicholas: And they're [the two quantities of air - represented by lines] almost there, like close to each other, and this is the part [Frame 7 in Figure 37] where it can't go any further, and that's why it's stuck right there.

Interviewer: And that's what you can feel with your hands?

Nicholas: Yup.

As Nicholas described the two representations of air coming together in the midpoint of the connecting tube (see Frame 7 in Figure 37), he made a gesture to further illustrate his thinking. He slowly moved his hands toward each other as he described Frame 6 and said, “They’re almost there” (see Figure 38.A). He then described Frame 7 by saying, “And this is the part where it can’t go any further,” while he created another gesture that mirrored the symbol he included in his animation (see Figure 38.B).

Frame 5 Frame 6 Frame 7

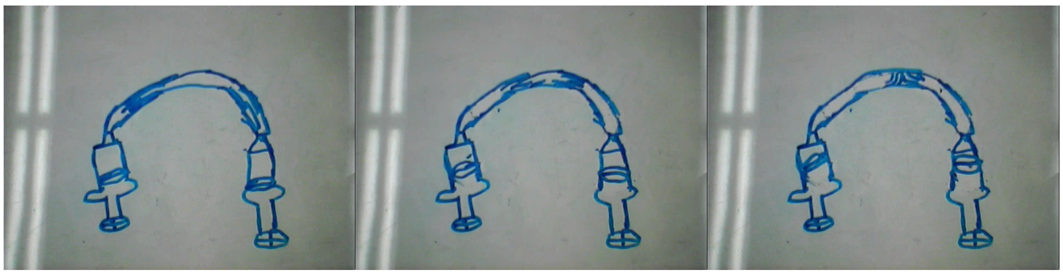

Figure 37. Three frames from Nicholas’ animation showing compression (coming after the first four frames shown in Figure 36).

A. “They’re almost there” B. “And this is the part where it can’t go any further”

Figure 38. Nicholas’ gestures. (A) Showing the two quantities of air “almost there” (i.e., in the middle of the connecting tube), and (B) showing what happens when they could not “go any further.”

The symbol at the midpoint of the tube denoted the point at which the two quantities of air met (also demonstrated through his gesture), and Nicholas was asked to describe that symbol in more detail.

Interviewer: So, how come the lines, you showed the lines going up [see Figure 37 - Frame 7]. What were you trying to show?

Nicholas: Like, how they're, like, if you was squished, you would be like, like...a crash, like boom [gestures two open palms coming toward each other and hitting - making a "smacking" sound] and then it would have been like stuck together.

Interviewer: Okay...So, what if we made one more picture, what would it look like as we let go?

Nicholas: Um, it would, these two [the symbols for air] woulda went down and the air would have came back into where it is [in the syringes]...

Nicholas elaborated on the ideas of "squished" (i.e., compression) by describing the moment the two quantities of air meet in the connecting tube as though they are two massive bodies colliding ("like...a crash, like boom"). The collision he envisioned explained why the air gets "stuck together," and thus why the plungers stop. The medium of animation, specifically the frame-by-frame depiction of compression, facilitated Nicholas' explanations about specific instances of the process shown in his representation. He used a myriad of expressive media -

verbal language, symbols drawn in his animation, movement of symbols from frame-to-frame in his animation, and gestures - to build a coherent story for compression. He explained how the air gets "stuck" in the midpoint of the tube, and how the air is "squished" when compressed, which causes it to go "back into where it is" (i.e., the syringes) when the plungers are released. Each of the means of representation - symbols, gesture, verbal language - are intimately connected in his attempts to make sense of compression and to build coherence in his descriptions of the process. His gestures elaborated the symbol he drew for "stuck," which lead him to the term "squished" as an alternative way to describe compressed air. In turn, "squished" led him to describe and ultimately represent in his animation the air's resistance to compression, and its tendency to push the plungers out of the syringes when no longer compressed. After he created the last segment of the animation (see Figure 39), he said, "Well, the difference [between compression and "at rest"] is the air is squished together when you're pushing both of them together, so they're stuck. But when you let go, they go back into the tubes." His animation showed this with lines representing air

Frame 8 Frame 9 Frame 10

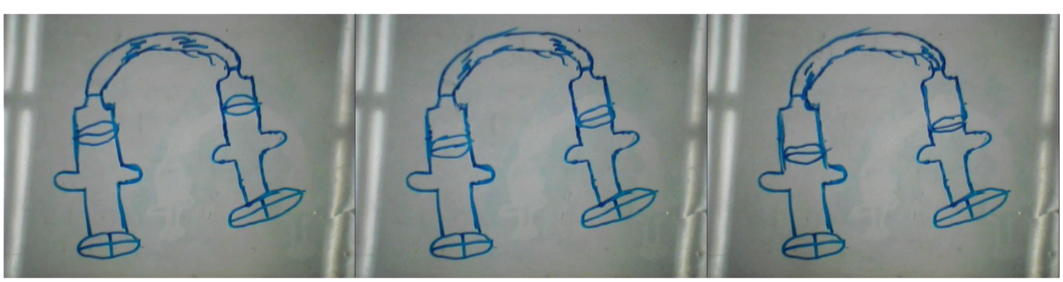

Figure 39. Final three frames from Nicholas' animation showing how compressed air moves back into the syringes when the plungers are released.

moving from the middle of the tube (see Frame 8 in Figure 39) back toward the syringes in three successive frames (see Frames 9 and 10 in Figure 39). His verbal explanation was clear, detailed, and succinct. Moreover, Nicholas' reasoning led toward the articulation of a mechanism that would help explain why air can be compressed, using ideas like "squished" and "stuck." While his descriptions included nascent ideas about mechanism, he still had work to do in articulating a coherent linking process to explain the relationship between cause and effect. The complicated interrelations between his verbal utterances, his gesture, and the frames of his animation allowed him to reason about compression with more precision; increasingly precise descriptions can lead students to articulate mechanisms that explain the causal relationships involved in phenomena such as compression.

It is interesting to note that an increased sophistication of one's reasoning can coexist with other non-normative beliefs, such as the two-quantity model. Nicholas exclaimed that there was air in the entire system (when describing air transmitting a force in the pushing case), which is seemingly in conflict with the two-quantity model which he focused on in the compression case (i.e., "*they* go back into the tubes," as if there were two different entities, simply meeting in the middle and then departing into the syringes). This highlights the importance of context in how students make sense of phenomena they observe, and how different resources are used to explain different aspects of what seems to be the same problem (i.e., reasoning about air and how it moves).

Nicholas was not the only student to begin using more precise verbalizations and reasoning about mechanisms for compression during the animation session. Tasha used line segments as a symbol for air in the first interview, but chose to use dots as a representation for air in her animation (see Figure 32). She demonstrated compression by increasing the concentration of dots in the connecting tube when the plungers were being pressed. She explained, “There’s too much molecules, and they’re smushed together, and there’s no more room.” The dots representation allowed her to vary concentration, thus, the representation she chose supported her reasoning about the amount of molecules and their relative spacing. Sarah used long line segments to show air in her drawings, and she opted to use short line segments in her animation (see Figure 32). Her explanation of compression was similar to Tasha’s; she said, “...all of the little, like, all of the, um, little things of air are being, are like squished in there and they can’t move or anything. And then after when you, um, let go, push back through.” She reasoned about her chosen representation in terms of a “squished,” or tightness of those “little things of air” when being compressed, and Tasha represented this idea in her animation by adding more dots to the connecting tube to show compression. Alternatively, Isis (see Figure 31, showing the evolution of her symbol use) chose to use dots, but she did not vary the concentration of these symbols in her animation (as she had in her drawing - see Figure 17). Instead, she reasoned about compression verbally and that included ideas about a mechanism to describe compression when she discussed the effectiveness of her animation for showing the compression of water. She said, "...water is not as flexible as air, because all the molecules are closer together." Having experienced the incompressibility of water, she reasoned that the difference between air and water was the relative spacing of molecules in each of these substances; molecules in air are farther apart than water molecules and thus air can be compressed easier than water. She had not explicitly included dot spacing in her animation, yet the representation of molecules allowed Isis to explain compression using ideas about spacing; her explanations show how a representation as simple as "dots" can support and enhance a student's constructing verbal and drawn representations.

Creating a stop-motion animation of one's ideas is a unique and relatively unfamiliar exercise for most elementary school students. However, the animation itself is essentially a series of drawings that when combined become a dynamic representation of one's thinking rather than a static snapshot, like a single drawing. Students are familiar with drawing their ideas, and thus animation is a natural extension of their representational capabilities. When reasoning about a complex idea like compression in gases, the ability to focus attention on how specific elements shift over shorter time intervals (i.e., from frame to frame) has distinct benefits for breaking complicated changes down into small snippets. Changing the drawing for each frame of the animation allows the students to narrow in on specific ideas and relationships between elements of the system, while also providing an inherent re-representational opportunity. Additionally, with an unseen like air, the process of generating symbols and inscriptions that materialize the “invisible” affords students chances to reflect and examine their thinking. As was the case with the students in this study, elementary school students in general tend not to understand the particle model in a normative sense (Johnson, 1998; Novick & Nussbaum, 1978, 1981; Driver et al., 1994). Yet, the substance of students’ reasoning in this study shows that despite little recognition of molecules as the building blocks of matter, students can invent and refine mechanisms with similar features as the normative models used to describe processes like compression. Students talked about air being “squished” or “pushed together” which is an intuitive idea with similar structure to condensing the space between molecules when compressing a gas. The students’ interpretations of an example representation, one in which dots were used to represent air molecules, demonstrates that they were “ready” to consider discrete representations of air (such as a particle model) to describe what they experienced with the syringes.

Critiquing example animations

At the conclusion of each session, students were shown example representations generated by other students for their critique and analysis (see Chapter 3 for more details). One of the example animations shown to the participants depicted air as small, square dots, and it illustrated compression by having the dots move closer together in the connecting tube as the plungers moved into the syringes (see Figure 40). The students (Isis, James, Nicholas, Norris, Sarah, Tasha) who represented air with discrete elements (line segments, dots, “people” - as with Norris) had not all arrived at a description of compression

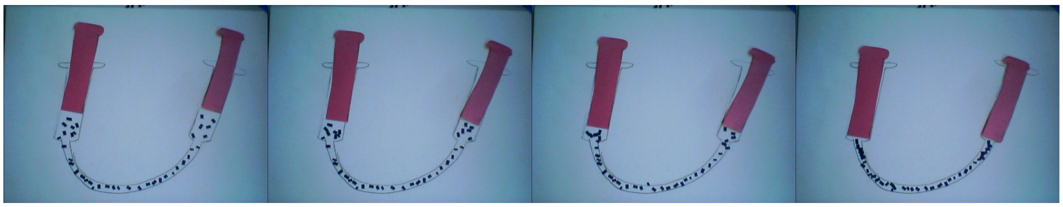

Figure 40. Frames from the example animation presented to students showing air represented as discrete elements becoming more concentrated under compression.

as a change in the spacing between these elements. That is, with the exception of Isis, their animations and verbal explanations had not explicitly included ideas about compression in terms of molecule spacing and density. Tasha and James included a higher concentration of dots to show compression, but they had not explicitly stated that these dots were closer together in compression, rather they used phrases like “smushed together” (Tasha). Inherent in those ideas of “smushed” may have been particles being closer together, but this had not been made explicit. For all these students, viewing and interpreting the example animation was both a conceptual and representational opportunity. They viewed this animation (see Figure 40) and made spontaneous connections to their own explanations, as well as pointed critiques of the animation, which depicted a rather complicated collection of ideas.

To start, students demonstrated an adeptness for describing what the animation was showing. For example:

Norris: "They're pushing it both together, and they go to the middle..."

Kandice: "...At first they separate, but then they close."

Oscar: "...They connect all together."

Tasha: "...When they're pushing, the air, the molecules go inside the tube together, and they get stuck."

Wanda: "The dots are...the dots are getting together."

They saw the animation as a representation of compression in the syringes, and all the students offered critiques of this particular way of representing the process. Most students approved of this model of compression, however, a small subset of the students (3 of the 12: Perry, Oriana, and Kendra) rejected the particle representation. For example, when asked if the animation did a good job showing compression Oriana said, "No, cause air's just like a whole bunch of air, it's not like in little dots or anything." Similarly, Perry at first said he liked the animation, but after watching it a second time, he said, "No, I'm wrong. It's just dots dots dots dots." For these few students, the task of assimilating this alternative representation of compression into their way of reasoning about the process was challenging. However, for the rest of the students, the sample animation was another way of showing what they had previously explained:

Norris: "I did the same thing, when, made it in the middle..."

Oscar: "You're just pressuring, the same thing."

Wanda: "...The same way that I explained it."

Isis viewed the example and immediately recognized the dots as representative of molecules ("she's showing the air by the molecules"). She went on to describe the animation in this way:

Isis: They get tighter and tighter and tighter.

Interviewer: What do you think about that?

Isis: I think that's the same thing that I was saying, because they get all close together, and then they have to spread out again.

Isis not only comprehended the example as a representation of molecules of air, but she also attended to the molecule spacing - relating it to her own verbal explanations offered earlier. Overall, 9 of the 12 students (Isis, James, Kandice, Nicholas, Oscar, Norris, Sarah, Tasha, Wanda) interpreted the example representation in some manner that supported or related to their own reasoning about compression. The literature on animations as demonstrations of dynamic processes presents mixed results in terms of how students perceive the mechanisms and processes depicted in the animations with which they are presented (Ainsworth, 2008; Morrison & Tversky, 2001; Tversky, Morrison, Bétrancourt, 2002). Furthermore, many researchers have expressed serious doubts that presenting students with animations can support reasoning or conceptual understanding (Tversky et al., 2002; Linn, personal communication, June 28, 2006). However, the students in this study had already produced representations of compression in more than one form (drawing, oral language, animation). They were producers (as opposed to viewers) of animations about compression, and as such their ability to comprehend this example was primed by their own attempts to reason about the process. In other words, they were equipped to analyze another external representation and to reason about the mechanism it displayed by having produced and reasoned with their own productions. The students' reaction to the example suggests they are (1) comfortable with external representations of unseens, (2) can interpret and critique representations of complex processes, and (3) that reasoning with their own productions may prime students to consider potential mechanisms that explain compression of air.

Building Compression

The third and final session of the interview sequence focused on students building physical devices to show their ideas about air and the linked-syringes. From a pre-selected collection of materials (see Appendix A), students explored how they could build a representation of some aspect of the linked syringes. This task was purposefully chosen as the final interview activity because building an explanation is an unfamiliar exercise for elementary-aged students in school settings (in spite of being one of preschool children's favorite activities, for instance in their block building or role playing and building specific scenarios for their dramatic play). It requires the student to not only conceptualize the processes under investigation (e.g., the pushing case, the compression case), but also to select materials to stand for particular elements of the system. With drawing and animation, students were afforded more freedom to invent or appropriate a symbol for air that represented their thinking about the syringes. The symbols they chose could show how air moves, how quantities of air interact, or could highlight particular features of the problem - such as with arrows and written labels; the constraints on symbol use in the drawn form were minimal. However, selecting a material that stands for another material (i.e., air), involves different constraints and a more challenging process of relating a representation to the idea or referent. Air is an unseen substance, yet students embarked on selecting a different, visible, material or substance that could stand for air. The chosen representation is subjected to the force of gravity, momentum, and is a visible object, all issues that challenged students' ideas about the composition of air. In other words, their implicit beliefs about air were made explicit in the process of having to select something that might stand for or show air. I contend that this challenge is a benefit of this particular form of representation, but it also confounded students' attempts to represent and reason about compression in this final session. The majority of students concentrated on how to "show air," which resulted in a focus on air as a substance rather than the mechanisms of compression. Yet, despite the difficulties students experienced, some students were able to build on their prior reasoning about compression from the animation session by using their constructions to explore and experiment with their thinking (see the chart of ideas and symbols for compression in Appendix D).

Building on prior reasoning about compression with physical artifacts

Students constructed a wide range of physical artifacts to support their reasoning about air in the linked-syringes, including compressing the air in the tubes. Following the animation session, many of the students had reasoned about air using a discrete representation (Isis, Nicholas, Sarah, James, Tasha, Norris), and many of them had arrived at the idea of "squishing" or "together" as a way to describe compressed air (Isis, Kandice, Norris, Tasha, Sarah). Yet, the two-quantity model of air (independent volumes of air in each of the syringes) remained the dominant model for explaining compression. With this model, the "squishing," "crowded," or "together" ideas that students introduced did not specifically address the material composition of air, as a space argument was evoked wherein "squished" was the result of a greater combined quantity of air than could fit in the connecting tube. However, the representational activity in this third interview required students to select a material that either stood for or showed air. The process of selecting a "stand for" material for air forced students to address the material aspects of the substance. In total, 11 of the 12 students (Isis, James, Kandice, Kendra, Nicholas, Norris, Oscar, Oriana, Perry, Sarah, Tasha) selected a discrete material (e.g., small metal ball bearings, corks, pieces of Styrofoam) to show air, and these representations supported some students' efforts to consider how air itself may be changing under compression, as the following results suggest.

Tasha expressed an interest in building something that showed the movement of “molecules” from one “tube” (i.e., syringe) to the other, and how the plunger can push the “molecules.” An interesting idea emerged in this session, during which Tasha described air and molecules together, saying, “The air is shoving the molecules to go into the other tube.” It appeared that she believed air and molecules may co-exist as separate substances in the syringes (a model commonly found to be employed by students, see Johnson, 1998a), whereby air pushes the molecules. Tasha used this idea to explain compression before embarking on building her device, saying, “The air and the molecules push together, and it gets stuck in one tube [the connecting tube], there’s too many in one tube to push to the other side.” It appeared as though movement and quantity of both air and molecules were the focal points of her reasoning, and Tasha went on to build a device that resembled one of the syringes (see Figure 41). Tasha selected ball bearings, saying, “These are molecules,” and used them in her device. She commented on how the ball bearings roll around inside the PVC, and mentioned how this is “kinda different” than molecules;Tasha described the motion of molecules by saying, “They just float around.” She was asked to specifically explain compression in her device, and she said:

> When you’re pushing it [the plungers] up like that, it [one of the plungers] gets stuck closer up to the tube [the plunger stops near the connecting

> tube] part, and it’s not gonna go anymore, because there’s too many molecules on the other side [in the connecting tube]. And, it gets stuck in this kind of tube [points to the connecting tube in her device].

In the animation session, she described compression as there being “no more room” in the connecting tube.

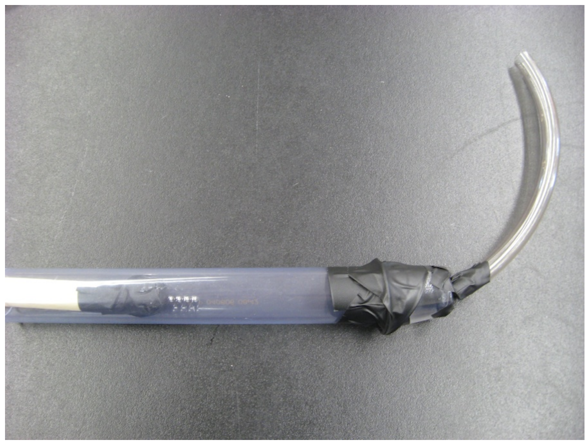

Figure 41. Tasha’s construction including a plunger made from a wooden dowel, a clear PVC syringe barrel, and a connecting tube attached with ball bearings standing for the “molecules” inside the linked syringes.

Her animation showed a higher concentration of dots inside the connecting tube during compression (see Figure 35), but she did not comment on particle spacing specifically. In this interview, the idea of “no more room” shifted a bit to be “too many molecules” in the connecting tube, resulting in the plungers stopping at a certain point. When she was pressed a bit on this idea, she commented that during compression, “they’re [the molecules] closer, when they’re [the plungers] pushed together, it’s [the molecules] closer together, and there’s more molecules in one tube [the connecting tube].” For Tasha, the artifact she built and specifically the selection of the ball bearings provided her with a means for explaining compression and a possible mechanism for why the plungers moved in to a point and stopped when being pressed simultaneously. The spacing between ball bearings became a way to explain “no more room” or “too many molecules,” which built on her earlier ideas from the animation session. In her animation, she used a higher concentration of dots to explain compression, and now this idea was elaborated on to show molecule spacing with ball bearings. Thus, Tasha was able to use physical representations of air and her earlier ideas developed in the animation session to articulate a more precise explanation that included ideas about a mechanism to describe compression.

In addition to Tasha, Isis (see Chapter 4) used her selected symbol for air (i.e., ball bearings) to reason about compression as spacing between elements, as did Sarah (described in more detail in Chapter 6). Overall, students exhibited the ability to successfully build artifacts that captured their ideas about air and compression and supported their continued thinking about the problem. In the drawing and animation sessions, students’ reasoning developed to a point where it began incorporating ideas about specific mechanisms to explain compression. Many of the students continued to reason about mechanisms as they constructed and refined their physical artifacts. At the most basic level, one finding from this third interview is that students are able to build devices to represent their thinking. Furthermore, the process of selecting materials that corresponded or stood for air as a substance supported students’ reasoning about what changes in air when it is compressed. For Tasha, discrete representations of air allowed for changes in the spacing between elements that in turn aided her efforts to articulate her thinking. Alternatively, students could have chosen physical materials that were akin to shading in a drawing, such as cotton stuffing, where the concentration of the material could have been varied; these representations of air might have had a similar effect on students' attempts to unpack the terms "squish" or "crowded" in terms of air. However, discrete elements were the most dominant representation for air chosen by the students in this study, and the physical arrangement of the ball bearings, cotton balls, corks, and Styrofoam pieces are what supported students' thinking. The affordances of physical materials are that they allow one to explore and manipulate the representation in the process of reasoning and making sense of compression, even if the student does not select a specific symbol for air, such as with Wanda.

In the first interview, Wanda's description of compression, and specifically why the syringes stop at a certain point was, "because the air has no where else to go." In the second interview, she evoked a competition for space argument, where air from each of the syringes was competing for space inside the connecting tube. She said, "One of the airs from this side [one syringe] is trying to go right there [connecting tube], but the other one [opposite syringe] is trying to do the same thing but they can't because both of them are trying to do the same thing, but it's hard for them to do it." When it came time to construct a device in the third interview, she built a replica of the linked syringes with two pumps connected to a single tube, which replicated the compression case. Wanda was asked to explain what her device showed:

> When we push the two air's up [one from each pump or syringe], the air, like, is inside here [the connecting tube] and then it's getting ready to go...come out. But it couldn't [in the linked syringes], cause it's like another tube [points to opposite syringe]. So the air's coming out from this [one syringe], and same thing from that [opposite syringe].

Her description of two quantities competing for space was elaborated with the assistance of the device she had built. Wanda was asked what she could do to show something about the air inside the connecting tube, and she suggested cutting a hole in the tube between the pumps so that she could attach an additional piece of tubing perpendicular to the connecting tube, with a single syringe attached to the end (see Figure 42); when the two pumps were pushed, the syringe plunger moved outward. She described this as, "The rest of the air is coming together...the big force of the air shoots out the [plunger]." For Wanda, the two quantities of air coming together in the connecting tube somehow gained "force" - as she described, "Air joining together, it gets all the force." Her device demonstrated this "force" that stopped the two plungers from moving in the linked syringes by showing what happens when the air has a place to go (recall earlier, when she said the "air has no where else to go"). Asked to describe "force" a bit more, she said, "[air] gets force it's own way...like, um, like if...if

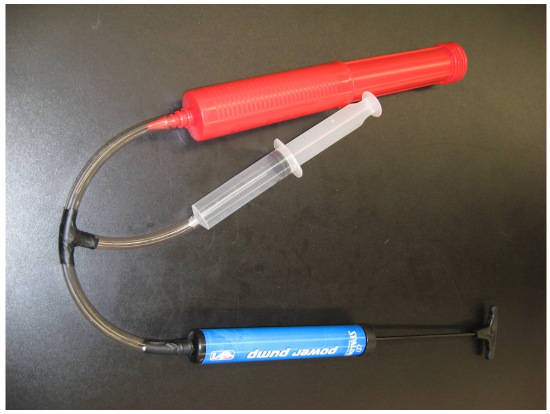

Figure 42. Wanda's physical artifact consisting of two pumps connecting to a plastic tube, with an outlet cut in the middle leading to a syringe.

they have more air, the more air they get the force they get." While this is a very different description of compression than that offered by the other students, it is interesting to note how she was able to construct a device to successfully capture this idea of "force" in the connecting tube (i.e., compressed air resisting applied force from the plungers in the linked syringes). She did not grapple with the challenge of selecting a physical material to "stand for" air, rather, she used her ideas about air's "force" to build a device that allowed her to continue describing compression in this way. Granted, her explanation of a process that linked cause and effect was rather imprecise, yet her achievements show a completely different approach to constructing physical representations. Thus, while selecting a discrete object to stand for air was a trend for the majority of students, Wanda was able to continue her reasoning and develop additional representations of compression without selecting a symbol for air. Her device allowed her to reason and think about compression, serving as a form of explanatory model.

Physical artifacts as working explanatory models

When a student generates a drawing or animation, that production includes a particular relationship between the idea the student is attempting to express and the particular symbols and inscriptions contained in the artifact. In that sense, representations on paper have a static quality when it comes to their role in reasoning. Animations are certainly dynamic representations of some idea, but the relationships between elements of the system represented in the animation are fixed at the point of production. They can be reasoned with and explained, but they are not dynamic in the sense that the original production is not altered after production. With physical devices, however, students can construct *working models* where explanations and reasoning become performances involving manipulation of the device in real-time to illustrate an idea or support verbal reasoning. With a working model, the variables of the system can be altered in real-time to demonstrate different ideas. As a comparison, an animation tends to be linear in its description of a device like the linked syringes. The students in this study first showed the pushing case, and then amended their animations to include compression. The particular cases of the phenomenon under consideration (i.e., pushing, compression) have one-to-one mapping with aspects of the animated representation. The same can be said for drawings. However, with a working model, the same representation of the syringes can be used to show pushing, compression, and possibly other ideas about air in the syringes. Varying the representation in real-time allows for students to use their devices as tools for reasoning. Explorations of devices like the linked-syringe, made by someone else and presented to the student, have similar exploratory and experimental qualities. However, the physical models that students build are representations of their own ideas, and what follows are examples of students in this study using their physical representations as working models that foster reasoning.

Figure 43. Oscar's device with two cups standing for the syringes, and ball bearings standing for air.

Oscar built a device with two paper cups that were connected with a clear plastic tube, in which he placed ball bearings (see Figure 43). When he was asked to describe specific scenarios with the linked syringe (i.e., pushing, compression), he configured his device to illustrate his thinking rather than offer verbal explanations. For example, he showed the pushing case by first holding one of the cups with all the ball bearings while asking me to hold the other cup. He raised his cup into the air, which caused the ball bearings to roll down the tube into the cup that I was holding; this was Oscar's demonstration of air in the pushing case.

To show compression, he again raised his cup and he asked me to raise my cup into the air as well, so that the ball bearings would roll to the middle of the connecting tube where they stayed (because it was at a point lower than the two cups). Interestingly, when demonstrating the compression case, he made sure that a few ball bearings remained in each cup (see Figure 43), to show that air remained in the syringes even if he pressed both plungers.

Oriana used the device she constructed, which mirrored the linked syringes with ball bearings inside a PVC tube with mock plungers on either side (see Figure 44), in a similar manner to Oscar. When she was asked to demonstrate the pushing case, she pushed on one model plunger and said:

> This is...[holds her device] can pretend as like the air [points to the ball bearings], and when we push it [one of the plungers], this one [the opposite plunger] like, this one like goes like that other one [the plunger on the actual linked-syringes] goes down, and when we push the other one, this one goes down.

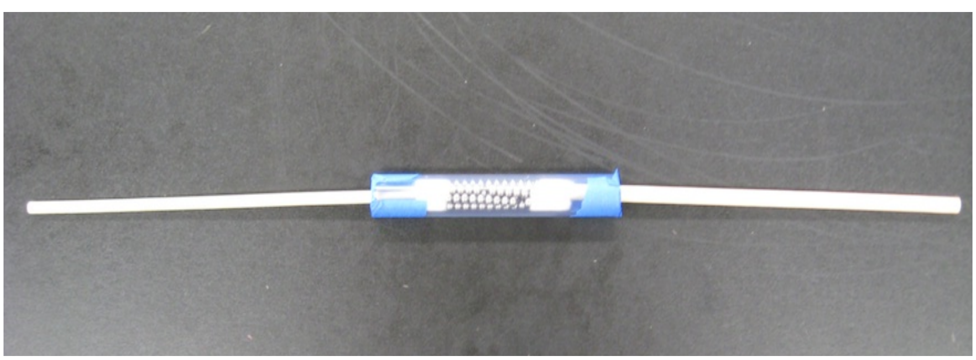

Figure 44. Oriana's device using ball bearings to show air, and two cotton-ball and wooden dowel assemblies as the plungers on either end of a clear PVC tube.

She described the pushing case in the linked-syringes containing air using her device to illustrate the process. However, when asked to show compression she noticed that the way her device was configured prevented the model plungers from being pushed in any farther (because the space in the PVC tube she was using was completely occupied by ball bearings packed together). She moved the plungers out so that the ball bearings were not as tightly packed, and she was asked how pushing the ball bearings together could resemble compression. She replied, "Yeah, because um, if you push them both, the air just goes down [into the connecting tube] and just goes (from) both sides [the syringes]." Again, a simple manipulation of her device allowed her to explore the relative spacing of the ball bearings, which illustrated compression in the linked syringes.

Overall, five of the twelve (Isis, Kandice, Oriana, Wanda, Oscar) students built physical devices that allowed for this dynamic manipulation. The opportunity for real-time manipulation of their devices allowed them to explore different ways of reasoning about and explaining compression. However, not all students' ideas about compression were necessarily clarified or expanded as a result of being able to demonstrate ideas like pushing or compression (see Appendix D). Thus, while the models possessed the potential for further reasoning about compression, not all students spontaneously engaged with more sophisticated ideas; the opportunity to further explore mechanisms that explained compression afforded by their device did not necessarily lead to more sophisticated reasoning. This may be suggestive of a slow process of adopting and reasoning with new forms of representations, even if the forms may appear to the expert to contain elegant representations of air in the syringes.

While some students built devices that could be easily manipulated and reconfigured (in more than one direction), other students built more uni-directional devices that tended to demonstrate ideas like how air can push an object as opposed to representing a mechanism that explained compression (see Figure 45). These uni-directional constructions supported students' verbal

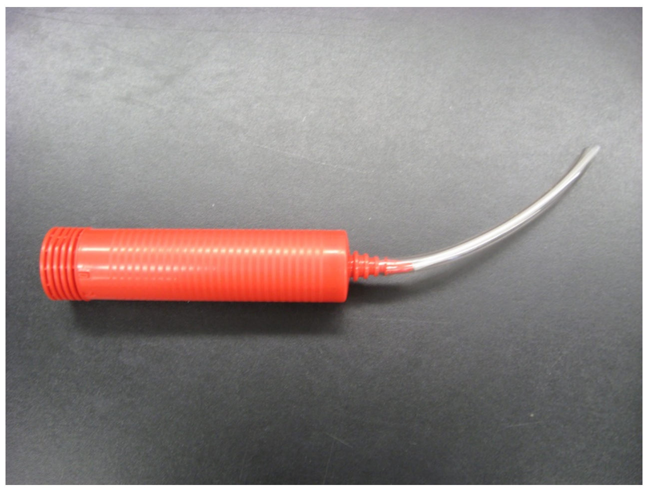

Figure 45. Perry's device showing how air from the pump can push ball bearings out of the tube attached to the nozzle of the pump.

reasoning, particularly with regard to the materials they chose to "stand for" air. However, their devices were less effective as working models through which they could have further explored compression, like Oscar or Oriana (see also Isis - Chapter 4; Kandice - Chapter 6). The examples of working models show that an attempt to represent one's understanding in the form of a physical model can provide opportunities where the models become tools for real-time exploration to support reasoning. However, to achieve this end, the selection of materials must support such manipulation, and as the findings suggest, selecting materials to “stand for” air and the syringes posed interesting challenges for the students in this study.

Reasoning about air as a substance as opposed to the process of compression

Students in this study demonstrated sophisticated and versatile abilities to reason about compression using the various representational forms employed. With both the drawings and animations, students’ reasoning progressed toward including descriptions of mechanisms that were captured in their representations. However, the coherence that was built around explanations of compression was less prevalent in this third session (see Appendix D) than in the previous two sessions. Despite the example of Tasha above, and the tendency for students to use their physical devices as explanatory models, most of the students in this session focused their attention on the particular representations of air in physical form, as opposed to ways of explaining the phenomena they experienced. As discussed earlier, the constraints placed on students generating a physical artifact to capture their ideas and thinking are much greater than those placed on drawings or animations. Choosing a material to “stand for” air is a difficult task, especially considering that students’ ideas about air are in considerable flux. The process of selecting a physical object that must stand for a separate, invisible object forces implicit ideas about the material composition of air to become more explicit through the comparison of the representation with one's ideas of the material nature of air as a substance.

The elements students chose to show air served different roles. Some students used the elements to simply demonstrate how air can push on and move objects (i.e., using a pump to push ball bearings, such that the ball bearings could indicate air's ability to push things). Other students contended that the ball bearings, corks, or cotton balls could be a representation of air itself. Those students willing to consider ball bearings as air itself were able to critique their own representation; many of these critiques were comparisons focused on the size of their representations relative to air.

> *Isis*: "They're really big compared to the molecules."
>
> *Sarah*: "Air's bigger than that."
>
> *Tasha*: "They're smaller [air "molecules" as she described them are smaller than ball bearings]."

Notice that comparisons of size went in both directions, molecules of air are smaller than ball bearings (Isis, Tasha), or because "air is everywhere", the discrete representations of air are too small because air is "bigger than that" (Sarah). Another dimension to students' comparisons, and the most prevalent, was the visual and tactile nature of the representations relative to air.

> *Nicholas*: "You can see them...you can feel them."
>
> *James*: "You can feel them, see them, and they're hard."

Oscar: "Air, you can't really see it."

While many of these ideas had surfaced earlier in the interviews (e.g., the "invisible" nature of air), articulating these differences lead some students to describe structural differences between their selected representations and their ideas about air. Oscar used ball bearings as a representation of air, and when asked what about air the ball bearings showed, he responded, "They really, they flow...they just go like that." As he said this, he showed how the ball bearings could roll down a clear plastic tube to simulate air moving through the connecting tube. Isis made a similar statement about the ball bearings in her device, saying that they, "show that there is air that moves through." Rather than compare the ball bearings to air as a substance, these students were able to compare how the ball bearings illustrated air's movement in the syringes. Other students talked about how "air is everywhere" (Oriana), and thus a collection of ball bearings did not accurately represent that idea about air; still others talked about air "floating around" (Isis, Tasha), which the ball bearings did not do either. Overall, the materials that students chose to represent some aspect of air facilitated comparisons between those elements and their ideas about what air is and how it moves. Students selected discrete elements to show different aspects of air (to demonstrate motion, to capture the particle nature of air, etc.), but ultimately were able to use these physical elements to reason about the composition of air, and the processes inherent in the linked syringe device.

Students' selection of particular materials to stand for air is illustrative of a bigger challenge students faced articulating the material composition of air. Without a model for the material substance of air, it was difficult for students to generate mechanisms that would describe air's compressibility. Students must reason using whatever understanding of air they have, regardless of whether they have ideas about molecules or particles. Despite this challenge, the students in this study used ideas that involved spacing of elements and the relative "squishing" of air under compression, which are all positive steps in terms of reasoning about mechanism and devising a way to describe compression. I contend that while these ideas were non-normative, their reasoning possessed strong parallels to the particle model, and thus an introduction to the idea of matter consisting of particles might help them explain why air can be compressed while water cannot. As Duckworth (1996) suggests, students construct understanding and when they are ready for a new model of explaining the world, they can adopt and appropriate this model. The results of this study (and particularly the case of Isis - see Chapter 4) suggest that students who have not encountered the particle model of matter may construct ways of reasoning about compression in the context of the linked syringes that prepare them to apply the particle model to make sense of compression.

Chapter 6. Diverse Representational Trajectories

Children reason and think in different ways; they use different resources and skills to make sense of what they see and to represent those ideas in different forms. The evidence from this study illustrates the diversity of trajectories that students traveled while developing explanations and representations of air, examples of which are illustrated in Figure 46. This chapter highlights similar ideas used in very different ways, which characterizes the particular trajectories, or pathways, of three students: Norris, Kandice, and Sarah.

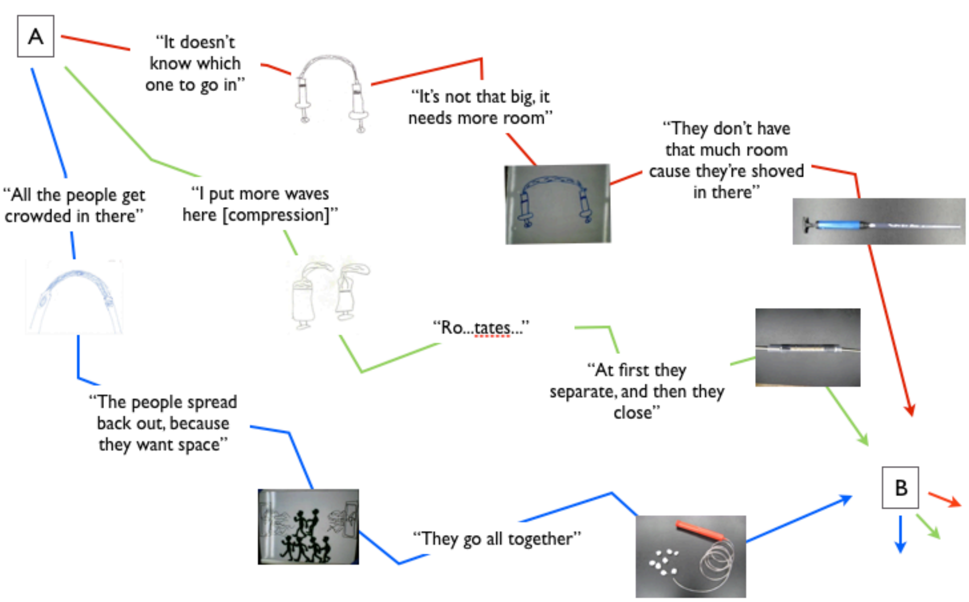

Figure 46. The diverse "trajectories" (or pathways) followed by students as they reason about and represent their ideas about air over the course of three interviews.

To begin, it is important to clarify the use of the term "trajectory." The choice of this term is not intended to imply a causal relationship between the particular microgenetic interaction and the ideas students expressed. It is conceivable that the ideas uttered and represented at the end of the interviews were ideas students already possessed (or could have been activated) before beginning this process. Rather, the intent of this chapter is to explain and communicate the differences in how students reason and construct representations, and how the process of production and refinement can help students develop more precise and coherent explanations of the science they encounter. I use the term "trajectory" to refer to the particular characterizations of the shifts in students' ideas over time in a similar the way in which Wiser et al. (2009) use the term "learning trajectory"; the representation of these unique trajectories are captured in Figure 46. In this study, the "trajectory" is comprised of the students' interrelated ideas and representations within the microgenetic interaction. Diverse trajectories are the particular pathways, directed by the students and their own reasoning, that does not suppose a particular start or end (as illustrated in Figure 46, with the "trajectory" lines continuing beyond "B," which was the endpoint of the interviews).

This chapter presents vignettes of three students, Norris, Kandice, and Sarah, and elements of their particular trajectories as means for illustrating the diverse pathways that students travel (captured in a chart at the end of the chapter as well). These three students were chosen because while there are similarities to the explanations they constructed, their individual trajectories are marked by differences in the productions they produced and the ways they developed their reasoning about air. I conclude the chapter with a short discussion of the hallmark characteristics of each student's particular trajectory relative to the similar ideas used by all three students.

Reasoning with Everyday Ideas

The literature on students' ideas about air tends to treat their understandings as knowledge or models that are acquired as a unit; students either know something or they do not. As Hammer et al. (2005) argue, thinking of "knowledge or ability as a *thing* that an individual acquires in one context and may or may not bring to another" treats students' understanding as a *unitary ontology* (p. 92; see also Hammer 2004). Many studies on students' ideas about air and particles focus on what students either "know" or "don't know" (Driver et al., 1994; Lee et al., 1993; Séré, 1982, 1986; Stavy, 1988); they focus on comparisons between students' understandings of matter and particles and more canonical ideas such as the kinetic molecular theory. While these contributions are helpful in shaping the ways in which we think about what students' bring to different learning situations (see Smith, diSessa, & Roschelle, 1993), they tend to shift the focus toward *accuracy* of students' ideas, rather than usefulness or productivity. The students in this study uttered many of the conceptions reported in the literature, for example that air weighs nothing, that motion is a requirement for the existence of air, or they offered descriptions of pressure as "too much" or "stuck" (see Séré, 1985). Consider the ubiquity and relative ambiguity of air in everyday contexts and conversations, and place yourself for a moment in the position of having to disaggregate a massive collection of ideas related to one word, “air.” If we are sympathetic to the challenge students face when making sense of words and ideas they have encountered for years, are claims of what students “know” and “don’t know” about air productive? What do we learn about their ability to reason, to think, or to develop representations of their experiences if the metric against which we judge their responses is *accuracy*? Instead, this chapter explores how students construct their explanations about air alongside their external representations, and how the process of producing representations offers each student unique opportunities to make sense of “air.” Whether or not students’ ideas reflect canonical ways of conceptualizing gases, such as air, they all began reasoning about air in the linked-syringes with whatever resources they possessed.

What Do Students Know about Air?

When asked outright, “*What do you know about air*?”, Kandice and Norris responded with statements about humans needing air to breathe and live.

> *Kandice*: “People breathe it.”
>
> *Norris*: “We breathe ... we need air to live ... if we don’t have air to live, then we won’t talk or anything.”

In addition to ideas about breathing, students expressed ideas about wind and weather:

Sarah: "Wind can make things move, because it has a lot of power"; "Air is formed by wind"; "Air is made of rain...because sometimes when the wind blows, you feel wet stuff coming down on you..."

Kandice: "It moves in fall, they [air/wind] move the leaves."

Norris: "Cause air, like, the air, you can feel wind...air, wind is kind of made from air...when wind comes, it's like air is there too."

Norris, Kandice, and Sarah are a subset of the study sample, but the ideas they offered in these initial moments of the first interview were representative of the sample as a whole.[34] The ubiquity of the term air (similar to words like "force" or "light") makes it a difficult idea for students to make sense of in new (and unfamiliar) contexts like the linked-syringe device. As such, it is no wonder that when asked to make sense of air, students are challenged and offer convoluted and multidimensional explanations; they have a lot to say about air. While there is similarity between the ideas offered by these students at the beginning of the first interview, the individual paths of producing, reasoning with, and refining representations of air in the linked-syringes over the course of three interview sessions varied.

As the students progressed through the interview sessions, their ideas and representations evolved. As with any sustained engagement with a particular

[34] A few students mentioned ideas about air being made of oxygen (such as Isis - see Chapter 4); however the responses from Sarah, Kandice, and Norris capture the general trend for students in this study.

topic, especially in a one-on-one setting, it is expected that students' ideas would develop and that their explanations would change, possibly gaining coherency. Interestingly, there were similar features to Norris, Kandice, and Sarah's idiosyncratic trajectories: (a) their representations of air transitioned from continuous to more discrete symbols (see Appendix D); (b) they were able to reason about mechanisms to explain compression (see Chapter 5); and (c) they gained comfort selecting and reasoning about different representations of air, treating the representations as conceptual objects in their own right. Furthermore, the students featured in this chapter all developed versions of an explanation of compression that involved discrete elements becoming more "squished" together under compression, than when not being compressed. That is, the mechanisms these students described focused on the spacing and amount of *parts* of air (not necessarily molecules) as means for explaining the compression case (both the plungers stopping when pushed together and air's resistance to compression resulting in the plungers moving back out when released). For Norris, Kandice, and Sarah, the ideas they initially expressed were similar; regardless of particular origin (i.e., everyday experiences with wind or ideas about oxygen obtained in school). And, the ideas articulated in their productions during these sessions (e.g., "squished") also had similar characteristics. Yet, the particular ways in which they reasoned about these ideas, how they constructed representations, and how they explained their particular productions varied. That is, Norris, Kandice, and Sarah began and arrived at similar places, but the trajectories for each student were remarkably diverse.

Norris' Trajectory

Norris began the first interview session describing ideas about air that were consistent with the other students in the study. He described his ideas about wind saying, "...You can feel wind...air, wind is kind of made of air...when wind comes, it's like air is there too." For Norris, air and wind appeared to be overlapping ideas. When asked to put something on paper showing these ideas about air and his ideas about the linked syringes, Norris expressed uncertainty with what he could draw to show air. He suggested drawing "a fan, pushing." When asked how he might be able to show air in his drawing, he added lines on the left-hand side being blown away by the fan (see Figure 47.A). He described the lines as tassels hanging from the underside of a tablecloth on a dining table (presumably something he had seen at home or elsewhere).

As with his descriptions of wind blowing objects outside, his first drawing represented air blown through a fan to move another object. Norris chose to represent air by focusing on the *effects* of air on other objects, an idea captured in later productions as well. When talking about the syringes, he used ideas about wind pushing on things. When asked to put something on paper, he focused not on the syringes but rather on experiences he had with air moving objects. To probe his thinking around representing air on paper, he was asked to show air in a closed

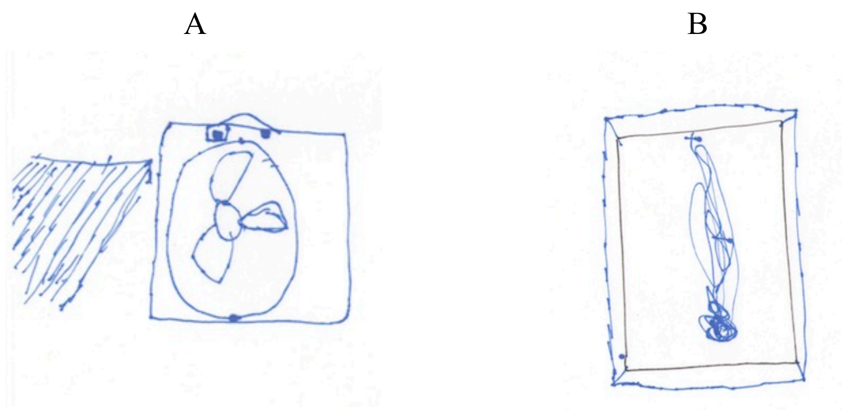

Figure 47. Norris' drawings. (A) His first drawing showing a fan to which he added the lines on the left-hand side after being asked to "show air"; (B) His second drawing of air inside a closer container. He added rough lines around the outside of the box to highlight the "closed" nature of the box, and talked as he drew the blue lines showing the path of an object.

container. This task challenged Norris, and he felt compelled to define the problem in more detail by drawing lines around the edge of the box to indicate "that we are looking into a closed box" (see Figure 47.B).

Interviewer: So how do we see the air that's in here?

Norris: Say if you put something in there, and it, it's like right here [points to a spot on the drawing where he drew dark blue scribbles] and then the next day it's right here [points to another place in the drawing where he drew blue scribbles].

Norris' second drawing focused on an object in the box that was displaced by moving air. As he described the object being in one place at one moment, and another place at a later point in time, he drew scribbled lines in the box. I interpret the drawing to show the path of an object in the container that could have been moved by the air inside, rather than a representation of air itself. Again, his ideas about air, which are the basis of his external representations, are deeply integrated with wind, motion, and air pushing on things. Additionally, Norris continued to focus on demonstrating the effects of air in his drawings. His ideas about air on paper were further explored by presenting him with a representation of dots on paper.

Norris: The dots air, like the dot. Maybe they'll show you like maybe one dot was there and then it kept going all over the place every single day.

Interviewer: Okay. And, what do you think the dots are?

Norris: ...like maybe...coins...

The dots representation caused a moment of confusion for Norris, as he attempted to comprehend what the dots might represent. Rather than interpreting the dots as a representation of air itself, I interpreted Norris to be suggesting that the drawing showed a number of places where the same dot had been at different points in time. Just as he had shown the path of an object in his own drawing, perhaps he viewed the example representation as showing the location of coins, as he said, at certain instances. The way he interpreted the example points to Norris' attempts to represent the effects of air and how air is able to move objects. He used his ideas about air and wind to both invent and to comprehend representations of air on paper; but, he focused less on what air is and more on the effects of air on objects. Norris was asked to explicitly show something about air in the syringes, and he traced[35] the device and began drawing lines as he narrated his production (see Figure 48).

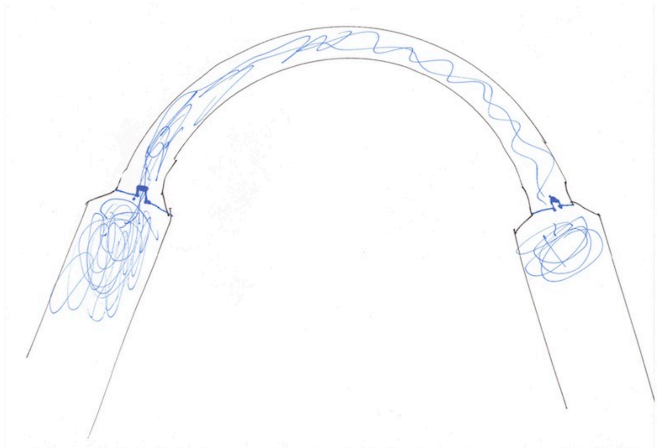

Figure 48. Norris' drawing of air as "people" in the syringes.

Norris: The air...it's like this...so it's like, so the, the air is like in here...so it doesn't, so it's kind of like people, say if it was people. The people were in here [left-hand syringe on drawing], they had to...someone maybe pushed them out, a lot of them go here, through the hole [in the syringe], throughout and go to the other side and fill that side. So then, when they push that one out [the right-hand syringe], they will go back to that side [the right-hand syringe].

Interviewer: Okay. So when they come over to this side [right-hand syringe], they [the people] push that other one [the right-hand plunger] out?

[35] Norris refused to draw the syringes free hand, as he said he was not a good drawer. I suggested he trace the syringes, and he liked that idea.

Norris: Yeah...so, it's kind of like they're in here [left-hand syringe], and then they get pushed out to the other side [right-hand syringe].

I believe Norris was challenged by the task of drawing air,[36] and the invention of "people" provided a context in which he could talk about air and represent ideas about air on paper. The way he generated the drawing was as if the paper was a performance space wherein Norris could experiment with ways of representing air. As he spoke, he drew lines coming from the left-hand syringe out of the nozzle and into the tube - "someone maybe pushed them [the people] out, a lot of them go here [connecting tube], through the hole." He continued to draw lines passing through the connecting tube, from left to right, until they eventually reached the right-hand syringe, as he said, "...and [they] go to the other side and fill that side." Norris' use of "people" as air allowed him to talk about air being pushed from one syringe to the other in a way that was comfortable and accessible for him. It also allowed him to draw lines that were presumably the path of the people, but also an inscription for air. "People" served as a powerful analogy for Norris, allowing him to reason about and represent different aspects of the problem, including the compression case.

Norris: If there are people here [left-hand syringe], the other people are already in here [right-hand syringe]. They get pushed

[36] As with many students; the idea of drawing something that you cannot see is challenging. For students who are less comfortable drawing abstract ideas, creating a visible inscription for an unseen posses a great challenge, and it is precisely the reason air was chosen as a topic for this study.

out, and it's crowded here [the left-hand side of the connecting tube]. And then they get pushed out [of the right-hand syringe] at the same time, but it's crowded in here [the right-hand side of connecting tube]. They [“people” on the right] won't have a place to go, ‘cause it's [the left-hand side] filled, and they [“people” on the left”] won't have a place to go ‘cause this [the right-hand side] is filled.

Interviewer: So, it gets really crowded in there [connecting tube].

Norris: Yeah, so it gets crowded, so then they have to, so then they stay in the middle.

As Norris generated his fourth drawing (see Figure 49), he again treated the paper as a drawing performance space, where he narrated a story about “people”

Figure 49. Norris’ drawing of compression, showing “people” on either side getting “crowded” in the connecting tube, where he drew a vertical line separating the two sides.

in the syringes as he drew. He began drawing circular scribbles in each of the syringes. He then drew lines coming out of the left-hand syringe going into the left side of the connecting tube while saying, “They get pushed out, and it’s crowded in here.” He repeated this for the right-hand syringe and the right side of the connecting tube. Once he had drawn scribbled lines in both halves of the drawing, he drew a vertical line in the middle of the connecting tube before going on to explain why the plungers resist a push when the air is compressed to a certain point. Norris called the syringes containing a number of people “filled,” as if to say the maximum amount of air was in each side of the linked-syringe device, and thus the plungers cannot move in any farther because there is no additional space for the people to go. Norris used his people analogy to talk about air and reason about a possible mechanism to describe compression, which he called, “crowded.” This idea of “crowded” related to an everyday idea of too many people in a small space, and it supported Norris’ making sense of compression and why the plungers stop at a certain point.

When he was left to invent a representation of air under his own direction (i.e., his attempts in Figures 6.2.A and 6.2.B), Norris expressed ideas connecting air with wind (e.g., the fan blowing tassels on a table, or blowing an object around in a box). However, when asked to explicitly attend to the syringes, he successfully invented a way of talking about air as a substance inside the syringes (i.e., “people”). This analogy helped to create a bridge between Norris’ ideas and his representations on paper. By using lines to show where and how "people" were moving in the system, he effectively manipulated that symbol (i.e., lines) to demonstrate his ideas about how air moved in the syringes. The usefulness of this analogy was further illustrated by his use of "people" in the critique of the example drawings. As he commented on the representations, he referred to lines and dots as "people" (e.g., "So the people could go in"; "make more people stay there"). In this interview session, the invention of a "people as air" context helped Norris express and articulate his thinking. It was a model that provided for flexibility and agility in the ways he described the phenomena demonstrated by the linked-syringes, first talking about people moving and then amending the description to include "crowded" as a means for describing compression. In the second interview, Norris again talked about people, but with a slightly different relationship between people and air.

The second session included an introduction to the animation medium and SAM Animation software (see Chapter 3). In this introduction, six plastic figurines (each representing a point in the walking cycle) were used to demonstrate how individual frames combine to become a continuous motion in movie form (i.e., the figurine taking a step forward). Seeing these figurines, Norris decided he would use them as "people" in his animation: "Like, when I draw like a big fan, and then the guys are like...take picture of the guys when the fan is on when it blows [them] away." Norris' again turned to a fan as a source of air in this session, and he went on to create his animation showing what he had described. After he drew one fan, he asked:

Norris: Can I draw, like, lines?

Interviewer: Yeah, you can do whatever you want.

Norris: So, I could draw lines to say it's air pushing out.

I interpret Norris' question as an indication of his hesitation to adopt a symbol for air itself (i.e., lines), but also a certain willingness to generate and use an external representation for air. In the beginning of the first session, he opted to show objects moved *by air* rather than air itself (e.g., showing the path traveled by objects blown by air). However, his "people" analogy in the drawing session assisted his efforts to create an inscription for air, as he drew lines to show "people" moving through the syringes. Here, the lines were used to show air itself, and the people became indicators of the effect of moving air. Norris

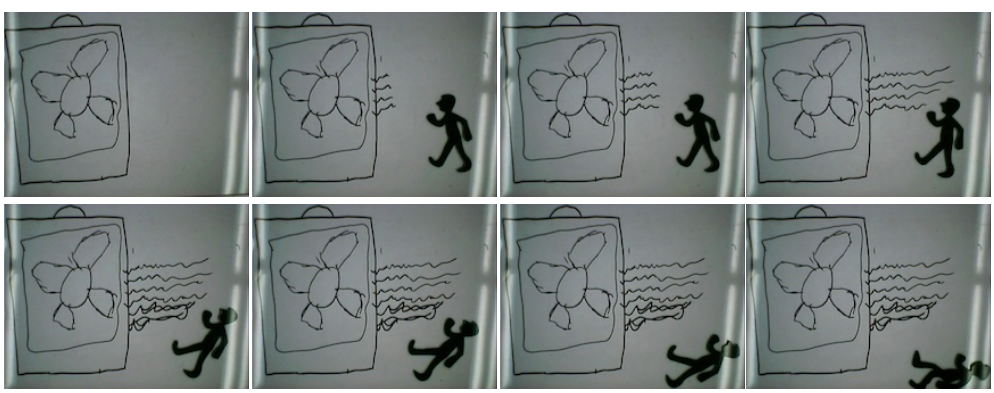

Figure 50. The first 8 frames from Norris' animation, lines showing air, increasing in length coming from a fan and hitting a figurine, which is knocked over (from vertical to horizontal).

proceeded to generate eight frames in his animation showing lines moving out from a fan, coming in contact with the plastic figurine that moved from a vertical to horizontal orientation (see Figure 50). He was asked to explain what he had shown in the animation, and he said:

> Like it's cold,[37] maybe it's, it's just normal air...it's pushing out, so when the guy, when the guy's, there's a guy up and then the fan gets stronger and stronger, and he's struggling, and then he falls over [gets pushed over by the air].

He explained that the air coming from the fan "gets stronger and stronger," and he showed this by making the lines from the fan get longer in each frame (see Figure 50) until they reached the figurine. Like in the previous session, I interpret Norris' statements and animation as evidence of his reasoning that air is related to wind and that air has strength. When asked what air consists of, he said, "Air is...maybe like, kind of, when it pushes, kind of wind," as though in the context of fans pushing people, wind and air are one in the same.

To show the compression case, Norris decided to draw two fans "pushing all the people together." He made a gesture to illustrate this idea by moving his hands far apart and them bringing them together to make a clapping noise (see Figure 51). Norris said he wanted to use the two fans, and to show how the air

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[37] Like other students, Norris interchanged ideas about coldness with descriptions of air and wind. I interpreted the use of "cold" as related to the timing of the interviews; January and February in the Northeast are cold months, and thus wind blowing on one's face, for example, feels cold.

Figure 51. Norris' gesture preceding the addition of frames to his animation to show compression. His gesture involved two hands starting about 2 feet apart (left) and moving inward (center) until the met in to make a clapping noise (right).

comes "out of the fan like we push air out [out the syringes]." Before he created additional frames in his animation, he was asked to describe how he would show compression.

Norris: They [the people] start out all over the place.

Interviewer: Kind of spread out?

Norris: And then the fan comes on, and they're still, they move a little, and the fan comes stronger and they're all bunched up together, and they all come together.

Interviewer: They all come together. Okay.

Norris: [nods head yes]

Interviewer: And what happens if we turn the fan off?

Norris: They'll go back. They will all probably get up [the people in his animation have been pushed over by the fan's air] and return back to their space.

Norris described how the fan would push the people together to make them "all bunched up," but that if the fans are turned off, the people will "return back to their space." He successfully captured this mechanism for compression in his animation (see Figure 52). As he generated the frames of his animation, he showed lines coming out of each fan getting progressively longer. He uttered, "The wind gets stronger" as he made the lines longer in each successive frame. All together, Norris added three frames to his animation to represent the compression case (see Figure 52), which he then described.

Figure 52. Frames from Norris' animation representing what happens when both plungers are pushed at the same time; people being "pushed all together."

Norris: 'Cause like, so this [one syringe] and this [the opposite syringe] are both of these [the two fans in his animation]. If we push this [one syringe], the people, some of them will go over here [to the opposite syringe]. If we push this, some of them go over here. If we push both of them [both syringe plungers] at the same time, they'll all go to the same place, and they will get stuck.

Interviewer: They will get stuck. Okay, and that's why we can't push it any more?

Norris: Hmm, hmm.

Norris' animation served as a model of the linked syringes with rather abstract representations of the major components in the device. When he said, "This and this are both of these," he meant that each syringe was represented by one of the two fans in his animation. The lines showed the air coming from each of the fans (i.e., syringes), and the people in the middle were pushed together, similar to how he described compression as "crowded" in the previous session. Norris' verbal explanations were precise, and he comfortably shifted from talking about the syringes to talking about his animation with little reluctance or hesitation. In his animation, the two fans were turned on and they pushed the people together in the middle, where they "get stuck," as he said. In this sense, the people are both showing the effects of air while also modeling the air itself since they were intended to show what was happening inside the linked syringes - even if Norris did not necessarily intend that to be the case. To complete his animation, he was asked to consider why the plungers move backwards when released after compressing the air inside the syringes. Norris created four more frames for his animation showing the people "returning to their space" (see Figure 53).

Figure 53. Four frames added to the end of Norris' movie to explain the plungers moving out of the syringes when released from the compression case.

In doing so, Norris erased the lines that were previously used to show air, and he moved the figurines further and further apart until they were spread out between the two fans. As he generated his animation, Norris was able to reason about a possible mechanism for compression in the syringes. His animated model provided him support in verbalizing his ideas about air and how air worked. Beginning with a single person showing an effect of air (i.e., being blown over), he continued by showing a group of people becoming “all crowded up” (i.e., compression), and by demonstrating how turning the fans off let them “return to their space.” The context created by thinking of air in the syringes as “people,” either as air (such as in the drawing session) or showing the effects of air (in the animation), allowed Norris to externalize his thinking. Additionally, the invented context provided Norris with a platform from which to describe a possible mechanism for compression in the syringes. The idea of compression as “crowded” people, where the individual elements (i.e., people) were closer together when compressed was an elegant and useful description of compression.

In the final session, Norris continued to work with this idea of “crowded,” as he built a device that pushed air from a pump (like the fan pushing air included in the previous two sessions) through a tube toward a collection of cotton balls on a table (see Figure 54). Norris was asked to describe how the device he built was similar to the syringes.

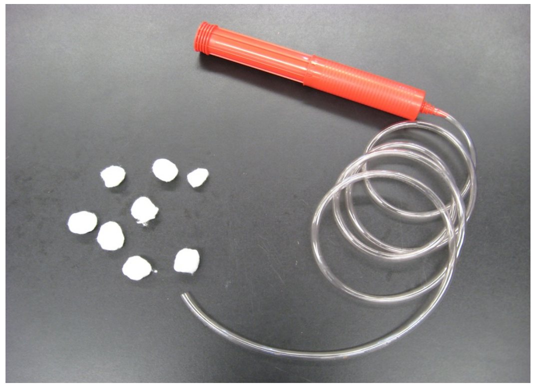

Figure 54. Norris' construction showing air from the pump pushing cotton balls, which were showing "people" and/or "air."

Interviewer: So, we're pushing the people around?

Norris: Yeah...

Interviewer: So, tell me how that's like the syringe?

Norris: It's like the syringe when, so, if they're [cotton balls] spread out, see? Spread out...it's like, like I said...[student begins blowing air from the pump, moving the cotton balls together on the table]...it's pushing them all together.

Norris used the cotton balls to represent people, which in turn represented his ideas about air, to show how when the syringes "push[ed] them all together." Thus, the same mechanism where a symbol for air (e.g., "people," plastic figurines as people, cotton balls) became "crowded" was used by Norris to describe compression. This idea first took the form of scribbled lines on paper, then included lines for air and people showing the effects of air in the syringes, and lastly was captured by the spacing between cotton balls in his physical construction. Norris' trajectory shows one particular arrangement of ideas, symbols, and representations used to describe air in the syringes at different times in the interview sequence. The hallmark of Norris' story is his commitment to the invented context of "people" as a means for describing and reasoning about air; a commitment that was strong and ultimately productive for his attempts to describe what he observed with the linked syringes.

Kandice's Trajectory

The ideas about air that Kandice initially expressed were similar to the other students in the study, and they involved notions of wind, oxygen as a necessary component of human life, and a relationship between trees and oxygen production (i.e., photosynthesis[38]). Her first descriptions of the single syringe were of the syringe pushing or pressing out air, which she could feel with her hands. When Kandice was presented with the linked syringes, she struggled to formulate verbal explanations of her thinking. She interchanged words like "control," "rotating," and "transforming" to describe the air going from one syringe to the other. Before each word, she paused for a moment (more than 20 seconds in some cases), and it appeared as though she was contemplating how best to capture her thinking in oral language. I interpret her explanations to be an indication that she was searching for words to reflect her reasoning, a consistent challenge for Kandice in all three interviews.

[38] It was interesting to discover that even though all the students in the study had engaged in lessons about photosynthesis in the 4th grade, their ideas [about what?] were incredibly fragmented and incoherent.

When Kandice began putting ideas on paper, she drew the linked syringes (see Figure 55.A), but she did not spontaneously generate a symbol for air. She was asked how she might show air in the syringes, and this prompted her to add a few short wavy lines, as shown in Figure 55.A. Her hesitation prompted me to ask her why it was hard to draw air, and she responded, “Because air is clear.”

The addition of the written label “air” to her drawing is indicative of her discomfort with generating a representation for an unseen. However, the representation she did create (i.e., the wavy lines) she said was intended to show “air moving,” once again relating ideas of air and movement as many of the students did. Now committed to this symbol, Kandice was able to appropriate it to

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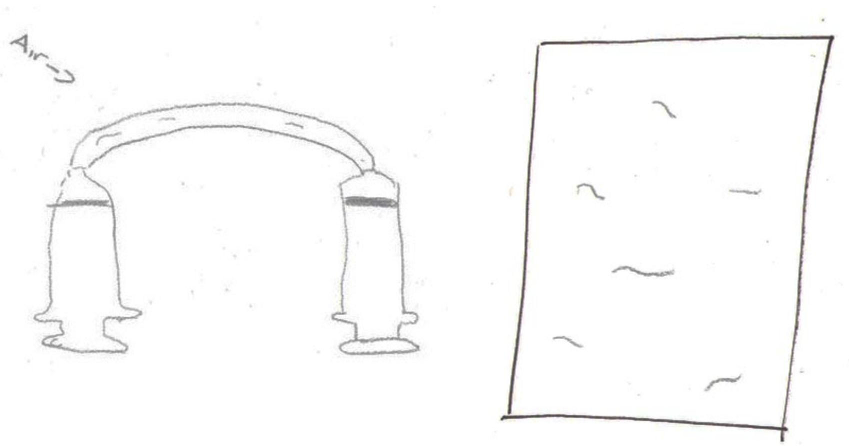

Figure 55. Kandice’s drawings. (A) Kandice’s first drawing showing the linked syringes, with short lines labeled with the word “air” which were later added to show air in the connecting tube; (B) Kandice’s drawing of air in a closed container, with “waves...like water” used as a symbol for air.

show air a box (see Figure 55.B), and later in her representations of compression. Before she created a drawing of her ideas about compression, we engaged in the following exchange:

Interviewer: And why do you think it stops when we press it? What's making it stop?

Kandice: The air.

Interviewer: Explain to me a little bit more about that.

Kandice: ‘Cause, it's too filled.

Interviewer: It's too filled? What do you mean by that?

Kandice: Like, if you have a...a bottle, filled with water, and if you push it in, it would stop, ‘cause there's no space...inside.

Kandice described compression as "too filled," and I interpret her analogy to a bottle of water having a finite volume as an attempt to articulate that idea.[39] She went on to generate a drawing that compared air in the compression case with ambient air (see Figure 56).

Her drawing showed two syringes with short wavy lines as symbols for air oriented in two different directions - vertically (see Figure 56 - right hand side) and horizontally (see Figure 56 - left hand side) - to demonstrate a difference between the two states of compression. She described her drawing in this way:

Kandice: This is one where you push it [compression] and most of the air, ‘cause I put more waves here [see Figure 56, left

[39] It is also interesting to note her comparison with water, before the water-filled syringes were introduced.

side of drawing], and most of the air is, like, everywhere. And this one [see Figure 6.10, right side of drawing] when it's not so...pushed...there's less air everywhere.

Despite her earlier reservations about generating a drawn representation for "clear" air, Kandice now not only created a symbol, but she also began to alter the symbol to communicate the difference between compressed and ambient air. As she said, the compressed air had "most of the air...everywhere" and in the ambient case "there's less air everywhere."

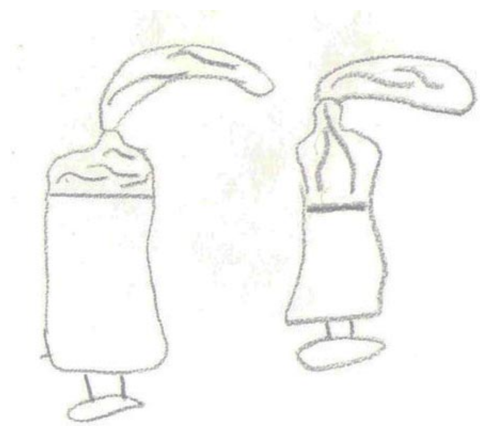

Figure 56. Kandice's representation of the difference between compressed air (left) and uncompressed air (right).

This distinction in quantity between the compressed and ambient conditions comprises the beginning of her reasoning about a mechanism to describe the compression case. Interestingly, when Kandice was asked to think about water-filled syringes, she described air in a manner contradictory to what she had just drawn:

Kandice: Because air is sort of like nothing...

Interviewer: Sort of like nothing. Okay. So we can press it in?

Kandice: Yeah. But, water...it's...it's like...it's almost like a [sic] object and you can't really push it in.

Kandice had just created a representation of air in the syringes, talking about the amount of air that was able to fit inside the contained volume, yet when asked what air was made of she resorted to “air is sort of like nothing.” I contend that this particular phrase exhibits the contextual nature of her statements; she had demonstrated beliefs about air existing, but when compared with water, “air is sort of like nothing.” Again, I consider this usage to be similar to how Grotzer and Perkins (2005) describe the “token uses” of phrases as placeholders for ideas not yet elaborated. In other words, lacking a means for conceptualizing air as a substance, Kandice resorted to calling it “nothing” in order to make a comparison with water. It could be that Kandice’s ideas about materials did not match her ideas about air, thus “air is sort of like nothing.” Either way, until she either invented or appropriated a means for describing (both orally and on paper) what air is made of, she remained challenged by attempts to articulate understandings of air as a substance.

In the second interview, Kandice generated an animation that focused primarily on the movement of air from one syringe to the other (i.e., the pushing case; see Figure 57). Interestingly, she did not include a specific symbol for air in this animation, which is further evidence of the challenges she faced earlier in selecting a symbol for air. When she was asked to show the compression case,

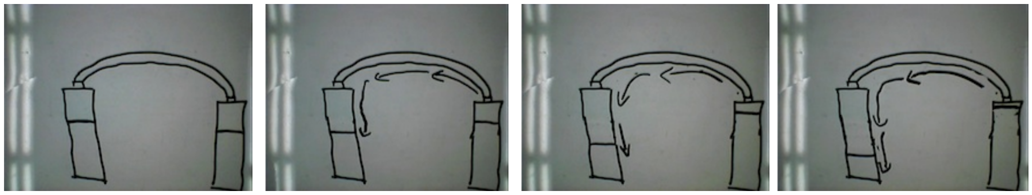

Figure 57. Four frames from Kandice's animation demonstrating the pushing case - where one syringe plunger is pushed in as the other moves out.

her reasoning from the previous interview - about differing amounts of air "everywhere" was abandoned. Instead, her animation included arrows (carefully placed *outside* the linked syringes) indicating the motions of the plunger: when they are being pressed inward and when they move back out of the syringes when released from the compression case. While she described the motion of the plungers, as represented in her animation, she was reluctant to describe a mechanism for compression (even though she had in the previous session). However, viewing the example animation (see Figure 8 - Example B) rekindled her reasoning about mechanism.

Kandice: Oh...at first they separate, but then they close [gestures with hands moving away, then back together again - see Figure 6.13].

Interviewer: Then they close, what do you think about that? What do you think that's showing?

Kandice: How the air...reflects when you push it?

Interviewer: Oh. Okay. So how when you push it and let go it reflects, you said? What do you mean, is there another way you could describe reflects?

Kandice: How the air...[long pause - 30 seconds] how the air ro...tates?

Kandice's gesture was a re-creation of the particular mechanism for compression illustrated by the example animation. The particular phrase she used to explain the mechanism in the animation, "at first they separate, and then they close," was descriptive, yet she continued to search for a single word to encapsulate the idea of compressed air. When pressed to relate that particular mechanism to the compression case in the syringes (which the animation was showing), she used the word "reflect," followed by the word "rotates." As with other points in the interview session, Kandice appeared to search for words to capture her reasoning. The ease (and excitement, marked by her elation as she created the gesture in Figure 58)

"At first they separate..."

"...but then they close"

Figure 58. Kandice's gesture describing how the air in the example animation "separates" and then "closes."

with which she comprehended and described the example animation suggests that this particular representation aligned with her ideas about compression; the mechanism of dots getting closer together when compressed made sense to Kandice. Yet, for unknown reasons, she appeared compelled to use technical words like “reflects” or “rotates” to capture her reasoning. She did not pursue more detailed verbal descriptions of the particular process, and instead attempted to find a scientific[40] word that would capture what she observed with the syringes. I interpret her selection of “reflect” as descriptive of the plungers stopping and moving back out when released; “rotate” was likely a synonym in this particular instance, generated in an attempt to clarify what she meant by “reflect.” Having seen this animation, which used a discrete representation for air and a particular mechanism for compression (spacing between particles), Kandice embarked on the third and final interview session.

Figure 59. Kandice’s constructed device showing her ideas about air and the linked syringes: cotton balls taped to wooden dowels using black gaffing tape, with corks inside showing air inside a clear piece of PVC piping.

[40] Alternatively, perhaps the words “reflect” and “rotate” came come from her experiences in mathematics classes, where these words are used to describe movements and rearrangements of objects in a geometrical sense.

Expressing an interest in building a device "to show the way the air is going when you push one [syringe]," Kandice began perusing materials to construct her physical representation in the third interview. She built two model plungers that were inserted into either end of a clear piece of PVC tubing, with a collection of corks between the plungers to represent air (see Figure 59). As she described the device, she mapped each element of her production to the linked syringes; she had built an exact working model of the syringes. Kandice appeared to be most interested in showing the pushing case with the device that she built - a case that her device illustrated rather elegantly. Pushing on one plunger pushed all of the corks together, resulting in the opposite plunger extending; she described the pushing case rather succinctly.

Interviewer: Okay. What do you think that does? Show me.

Kandice: [Student pushes her model plunger, which pushes the corks inside the PVC tube] It pushes the air.

Kandice used the device to show how pushing on one plunger resulted in the corks moving, as she said, "It pushes the air." Her use of the word air in reference to corks demonstrates her comfort with the representational aspects of her device: corks stood for air. Kandice was further asked to describe the compression case, and specifically what her device showed about pushing both plungers. She said:

> Like, how the air transforms...and which way it goes. When you push this one [linked syringes] you don't see the air moving, but if you push one of

> that [one of the plungers in her model] you can see which way the air [or corks] moved.

Kandice described the demonstration of compression using her device as "the same" as with the air-filled syringes, and she used the word "transforms" to describe compression in this instance. In her model, pushing both model plungers resulted in the plungers moving in a small amount, but stopping due to the corks in the middle of the PVC tube. This was "the same" as with the linked syringes. However, once again Kandice did not spontaneously expand upon her simple description. I probed her thinking in an attempt to elicit more detail in her reasoning.

> *Interviewer*: What do you think is between the corks? Is there any space between them?
>
> *Kandice*: There's space in between them. But in the air I don't think so...not a lot.

Kandice realized there was space between the corks when her attention was focused there, yet I interpret her response to indicate a discrepancy between her ideas about air and the spacing between corks; as she said, "But in the air, I don't think so...not a lot." Despite her selection of corks to show air, it appears her understanding of what air as a substance consists of remained ambiguous. Her earlier statement that "air is sort of like nothing" may be evidence that Kandice has yet to articulate ideas about the material composition (or material existence) of air; a challenge explained by her struggle to find particular words and phrases to describe the phenomena that she observed.

Like with Norris, it appears that Kandice has many ideas about air and the syringes in flux, but both her representations and her explanations about air evolved as the sessions progressed. While she was comfortable discussing mechanisms for compression in the drawing and animation sessions, she tended to focus more on the pushing case in this final interview, and on the suitability of corks as a representation for air. Additionally, Kandice's verbal explanations were fixated on particular word usage (e.g., "reflects," "rotates," "transforms"), and this perhaps posed a barrier for her in terms of expressing her thinking. Overall, Kandice's trajectory is quite different from Norris' (or any of the other students, for that matter), while it contained similar ideas (at least in part) and similar aspects of representations to other students in the study, which will be highlighted later in this chapter.

Sarah's Trajectory

Sarah began the first interview session sharing ideas about air that included "air is formed by wind," "wind can move water," and she mentioned that you can feel wind, but that "it feels cold." Sarah's ideas were similar to those uttered by other students in the study. In the first interview, focusing on oral language and drawing, Sarah concentrated her explanations and reasoning on the movement of air, using phrases like "blowing" and "air is moving" and talking about compression as the air getting “stuck” in the connecting tube. Her drawing included small line segments as a symbol for air in the syringes, which she showed throughout the connecting tube (see Figure 60). In the second session,

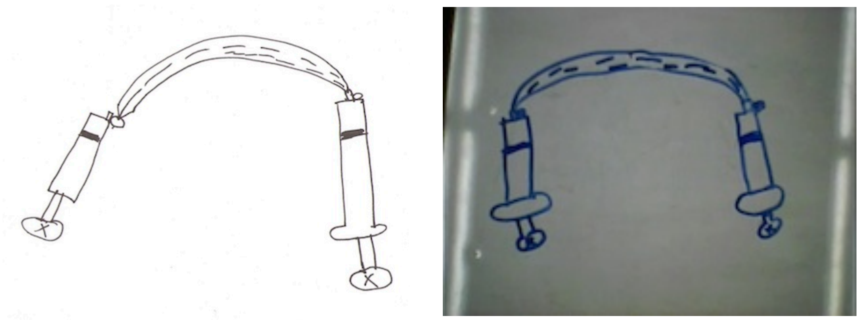

Figure 60. Sarah’s first drawing (left) and a frame from her animation (right).

Sarah’s animation resembled her earlier drawings; she used line segments to show air moving through the syringes and connecting tube (see Figure 60). However, her verbal reasoning about compression changed in this second session, gaining a bit more precision (as did many of the students’ ideas; see Chapter 5). When she finished her animation, she was asked to explain the compression case, and why the plungers move out of the syringes when released. She explained:

> *Sarah*: Because it's like all the, all of the little, like, all of the, um, little things of air are being, are like squished in there [connecting tube] and they can't move or anything. And then after when you, um, let go [of the compressed plungers], [the air] push back through [into the syringes].

Sarah's verbal reasoning included the idea of "little things of air" being "squished" under compression; yet, her animation did not contain an explicit depiction of this mechanism. When she was shown the example animations that did demonstrate a mechanism for "squished," using small dots of air (see Figure 8 - Example B), Sarah expressed disapproval and claimed that lines were a better representation than dots. She had similar critiques of the *dots on paper* representation in the first interview, saying, "You can think that's something else...like ants or something." Sarah resisted the dots representation of air, but appeared amenable to a discrete representation of air (e.g., "little things" of air), such as her use of small line segments. The substance of her reasoning about compression had evolved from the first session to now include ideas about discrete elements of air. However, it appeared that she was still developing a means for incorporating these burgeoning ideas when she produced her animation; the final session provided Sarah with an opportunity to refine both her reasoning and her representations of compression.

Sarah began the final interview by expressing interest in building something "besides" the syringes, so that we could "see the air a little bit going through [the syringes], or feel it." After she explored the materials available to her, she attached a short piece of PVC tubing to the end of a sports ball bump, and

Figure 61. Sarah's first device: a pump attached to PVC with a balloon on the end to show how the pump can inflate the balloon.

she placed a large balloon at the other end of the PVC, predicting that the pump would inflate the balloon (see Figure 61). Sarah tested her device and found that the pump, indeed, inflated the balloon, and then she offered an idea to amend her construction:

> *Sarah*: I wonder if I put those little things [ball bearings] in it, if they would push into it too.

She was asked what the addition of ball bearings to her device would show:

> *Sarah*: Um, that would show the air pushing those little things...it could be the little things of air, even though I said it wasn't dots.

Sarah placed ball bearings in the PVC tube of her device, despite having said, "[Air] wasn't dots." I interpret her continued resistance to a dots representation of air even while using ball bearings to be an indication of a slowly unfolding adoption of a discrete representation of air with smaller grain size than the line segments she used earlier. In other words, she used line segments in her animation, but she was reluctant in this session, perhaps because she thought the dots were too much of a departure from some idea that her line segments captured. However, the particular task (i.e., building a physical device) placed new constraints on the representational challenge: in order to represent air she was required to select a material that stood for air. In this case, she ventured to try smaller discrete representations of air by selecting the ball bearings. Yet, she qualified this decision by saying, "Even though I said it wasn't dots," as if to say, "I'm using these because they are available, but I am not certain they *really* show air." When she attempted to push the ball bearings into the balloon using the force of the air coming from the pump, only one ball bearing moved into the balloon. She described what that behavior showed:

> *Sarah*: Um...they're showing the air, like, the little tiny airs, like dots of air, but it will like go back in [to the balloon]...well one went in.

Before this point, Sarah emphatically stated that the ball bearings were selected to show air, "even though I said it wasn't dots." Merely a minute later, she was comfortable describing the ball bearings as "like dots of air." I interpret this change in her way of referring the ball bearings as further evidence of this slow adoption process. In her demonstration, the ball bearings did not behave as she had hoped, and Sarah realized that the air from the pump was not able to push the ball bearings all the way into the balloon. I used this opportunity to ask her how ball bearings may not be like air.

> *Interviewer*: And, so tell me how these things are not like air.
>
> *Sarah*: Hmm, because there's not dots of air, of airs. It's formed together, not in little pieces.

Sarah, again, raised the idea that air does not consist of little dots, but rather it is "formed together." Her ideas about the composition of air appeared to waver between discrete and continuous representations; however, I consider her comfort with alternative representations in thinking and reasoning about air to be a major accomplishment. She used ball bearings to illustrate the idea of air pushing, and was thus able to use this specific representation, while at the same time articulating how the representation was not like air. Having articulated that ball bearings were not a good choice of material to stand for air, she searched for an alternative and chose small pieces of Styrofoam that she placed in the PVC tube attached to the pump (see Figure 62). She said the Styrofoam pieces showed:

> *Sarah*: Them little pieces of air. I think it shows more better than little small balls.

Her newly selected Styrofoam pieces appeared to better suit her ideas about the composition of air, and thus her abilities to work with and refine representations to achieve a particular goal were demonstrated.

Figure 62. Sarah's construction: a sports ball pump with a long piece of clear PVC attached to the output, with small pieces of white Styrofoam in the PVC tube representing air.

Pleased with her new selection of material to stand for air, she tested what happened when she pushed air out of the pump. Pushing air from the pump in Sarah's device resulted in the Styrofoam pieces swirling around inside the PVC, moving upward as they spread apart. Sarah was asked how her device showed the compression case with the linked syringes, and she offered this explanation:

> Um...because air...is formed, not formed by balls. It's formed, like the little tiny little things, it's formed by these [points to Styrofoam pieces]...and it shows it much better. And, because when you push both of them [the plungers] in, air, when you push both of them [compression case] in like that, it [air] gets stuck and they [things of air] don't have that much room cause they're like shoved in there [the connecting tube], that's why they're [the plungers] not moving. But if we spread out [release the plungers], they [the air] come back in [to the syringes]. And you can see it. But if you spread it out, all the air that was in there [points to the tube connecting the two syringes], will go through to in there [the syringes].

Using her device, Sarah reasoned about a mechanism to explain the compression case: air is "shoved" into the connecting tube where it "don't have that much room," which results in the air moving out of the connecting tube and back into the syringes when the plungers were released. Her device contained a discrete representation of air that moved (when pushed by air from the pump) in a way that supported her reasoning about air being "squished" or "shoved" in the connecting tube of the linked syringes. She began developing a description of this mechanism in the second interview (while describing her animation), and the selection of the ball bearings and eventually the Styrofoam further supported her development of an explanation for compression.

The trajectory that Sarah followed was unique, as were all the students' trajectories, and it highlights in particular the arduous process of adopting and appropriating representations for an "unseen." Sarah was firmly opposed to "air as dots" until she saw a potential use for this representation (i.e., the selection of ball bearings for air, which allowed her to show how air can push objects). The slow, careful adoption (as opposed to a quick, spontaneous adoption) of the Styrofoam pieces illustrates the challenge many students face in developing and refining representations of their ideas. Sarah's trajectory, like others, also illuminates the myriad resources and ideas that students use as they construct, reason with, and revise their representations in different forms.

Comments on Students' Diverse Trajectories

The vignettes of Norris, Kandice, and Sarah illustrate the evolution of ideas and representations for each of these students during the three-interview sequence. A table comparing these different trajectories with the explanations and representations occurring in unique order is presented in Figure 63. Within this microgenetic interaction, students used similar ideas (e.g., air and wind, movement of air, relationship between air and breathing) to begin reasoning and generating representations of their ideas about air. However, the particular ways in which each student reasoned, explained, and represented his or her thinking were unique.

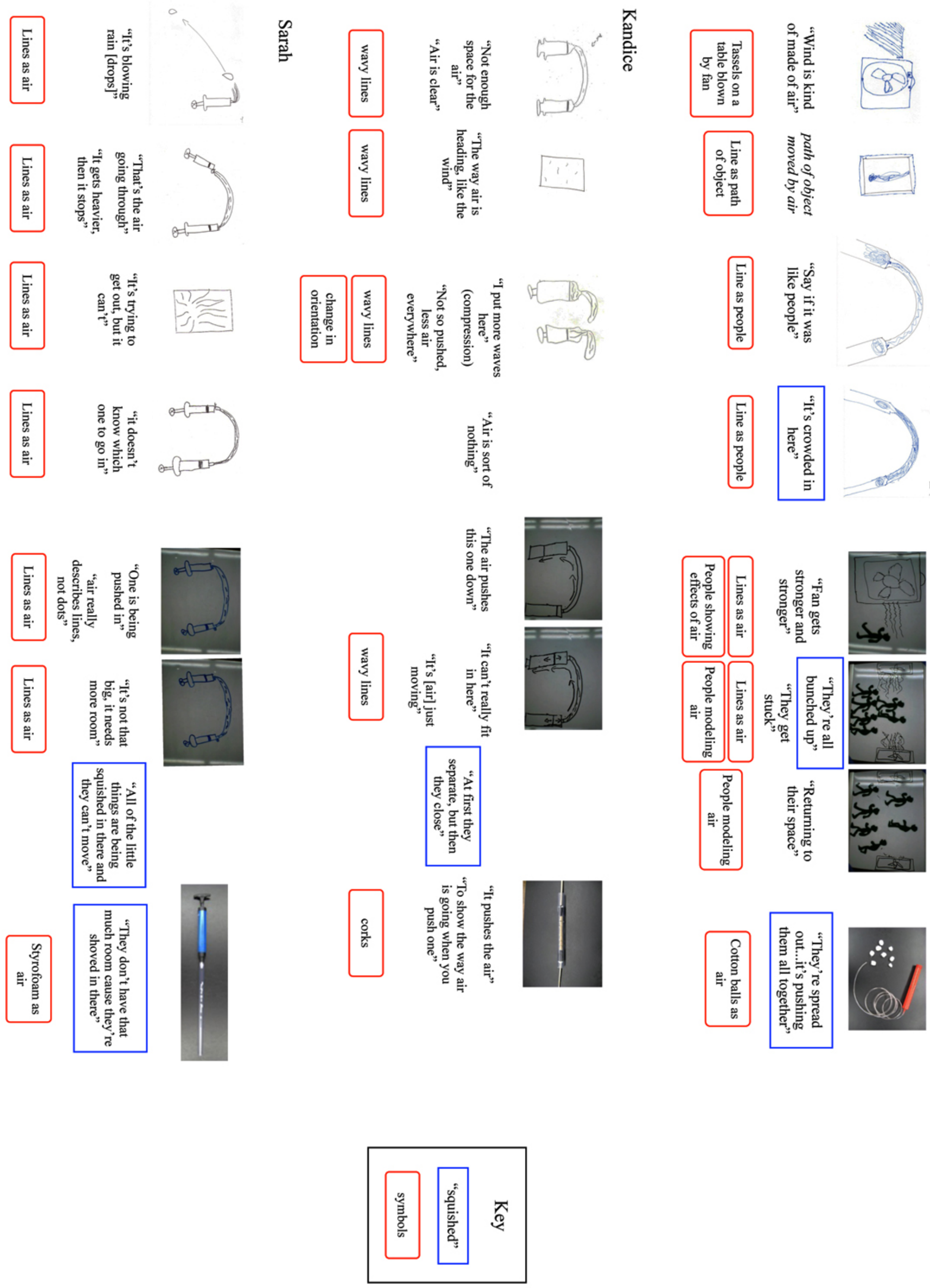

Figure 63. Chart showing the individual trajectories of Norris, Kandice, and Sarah.

For Norris, he quickly shifted his focus from air to an imagined context of "people as air" moving through the linked syringes. A shift from talking about air, explicitly, to talking about people appeared to ease Norris' comfort with and reasoning about the linked syringes. The analogy of "people" as air allowed him to introduce the idea of "crowded" as a means for describing compression. In the second interview, Norris' use of people showed both the effects of air pushing, as well as showing what happened to air under compression inside the linked syringes; Norris' "people" had a dual purpose. In both his representation of the pushing case and that of the compression case, he used lines to show air, and longer lines indicated the air gaining strength ("the fan comes stronger"). Compression was, thus, explained as strong air pushing the "people" together, and when the fans were turned off, the people spread back out again because they were returning to their space. Concurrently, he described the movement of the people in compression as though they were a model of what happened to air inside the syringes. From these instances, we can gather that Norris had a particular affinity for inventing a context, different from the focal point of the interviews (i.e., the linked syringes), within which he could reason about air and compression. His particular trajectory is marked by the introduction of "people," which served as a representation both *for* air and to *show* the effects of air.

Kandice's trajectory was marked by initial challenges finding both words and symbols to use for air, followed by increased comfort with describing and representing her thinking on paper. By the end of the first interview, she adopted a symbol for air (short wavy lines), and adapted that particular form (varying the orientation) to demonstrate the difference between compressed and ambient air. Interwoven with her adaptive use of symbols and representations was a search for particular vocabulary (using “reflects” and “rotates”) that captured her ideas. Throughout the interviews she was challenged by this search, and she used her representations - drawn, animated, or physical - to assist her attempts to describe and make meaning of air in the syringes. Viewing an example representation prompted Kandice to decide how to represent compression (the spacing between dots of air in the animation), and both her gesture and verbal statements indicate that the representation resonated with her. However, again Kandice attempted to find a single word to describe “squish,” rather than relying on more detailed verbal descriptions which she had demonstrated a strong capacity for earlier in the interviews. Her final construction was an elegant and sophisticated model of the syringes, using a collection of corks to “show air” in the syringes. Yet, her reasoning focused on showing air moving and differences between corks and air (on spacing between the corks: “But in the air, I don’t think so...not a lot”), as opposed to reasoning about specific mechanisms. Again, she opted for technical terms like “transforms,” rather than simpler descriptions, which characterizes Kandice’s particular trajectory through the interviews.

Finally, the story of Sarah’s trajectory through the interviews illustrates her early fixation on movements of air and representing this motion with lines. During the animation session, she began incorporating ideas about mechanism and ideas about pieces of air to describe compression in her reasoning about the syringes. The reluctance toward adopting a particulate representation of air that she displayed in the final session (i.e., ball bearings) illustrates the challenge of accepting a representation that is a radical shift from prior symbols. However, the eventual choice of Styrofoam pieces allowed Sarah to further articulate a mechanism that would describe compression: air getting "shoved together" where there was no more room (i.e., in the connecting tube). The adoption of the new symbol appeared to support her explanation of this particular mechanism, while also challenging her ideas about air as a substance. The particular challenge of selecting one material to stand for something else that one cannot see (i.e., air) poses benefits in making ideas about air explicit, while also serving as an analogous model of the linked syringes (this idea is discussed further in Chapter 7).

Overall, each student expressed different yet similar ideas about air and compression and used very different representations and patterns of reasoning. Some students built continuously on previous ideas (e.g., Norris); other students struggled to capture their thinking in verbal form and remained constrained by this challenge (e.g., Kandice); and still other students engaged in the tedious process of adopting and appropriating new symbols for air, a substance they could not see (e.g., Sarah). All told, the diversity of trajectories traveled by the students (shown in Figure 63) in this study illustrates the power of multiple representations: affording students the freedom to produce and explore representations in different forms provides them opportunities to reason about phenomena in personally meaningful and ultimately productive ways (i.e., their explanations evolved over time and through different representations; see diSessa 2004).

Chapter 7. Discussion

The results presented in this dissertation allude to a number of central findings that will be taken up in this chapter. Using the evidence presented in the three results chapters, I present a discussion of each major finding organized by the particular research question that each finding addresses. Table 1 includes all the findings (in generalized statements that are discussed in each section) organized by particular research question, pertaining to the students' who participated in this dissertation study.

Table 1

Major findings organized by research question

Research Question 1: What ideas about air and a particle model of matter are students able to represent across different systems of external representation?	
1	Students have many rich and complex ideas about air.
2	Students, while challenged by the task of capturing an "unseen" on paper, are competent producers and critics of representations of air that capture the complexity and sophistication of their reasoning.
Research Question 2: What are the relationships between students' productions in each of the representational forms and their understandings of air and the particle model?	
3	Drawing helped students organize the elements of the linked syringe problem, to begin developing more specific and precise explanations.
4	Animation facilitated students attending to specific points in the process of compression in the syringes to explain larger, observable changes.

5 Building physical models challenged students to select representations of air, but afforded them the flexibility to modify their representations dynamically, and to the use of their constructions as explanatory aides.

6 Repeated representations in different forms allow for re-description, which supported students' reasoning about a mechanism to describe compression.

Research Question 3: How are students' understandings of air and the particle nature of matter impacted by representing these concepts across multiple systems?

7 Students traveled diverse trajectories over the course of generating multiple representations, which provided them with opportunities to express and refine their ideas in individually meaningful ways.

Research Question 4: How is students' reasoning about science influenced by the production and refinement of external representations?

8 Students' reasoning about compression evolved from unidimensional verbal explanations to more multidimensional explanations over the course of the interviews.

9 While the literature on students' resources has discussed the role of context (Hammer et al., 2005), it has neglected to explore with any kind of depth the role of representational context (perhaps with the exception of Sherin, 2000), which the findings of this dissertation suggest can be crucial in how students make sense of science.

Research Question 1: What ideas about air and a particle model of matter are students able to represent across different systems of external representation?

1. Students have many rich and complex ideas about air.

Students in this study relied heavily on ideas about wind and air moving in their initial attempts to reason about and explain what was happening in the linked syringes; these ideas comprised only the beginning of their reasoning about air.

Considering the literature on students' ideas about air (Driver et al., 1994; Piaget, 1930/2001; Séré, 1982, 1985, 1986), a focus on wind, air moving, and air as a necessary component of life was expected. However, the conflation of ideas about air and wind in the students' initial verbalizations raises a bigger issue about the primacy and ubiquity of ideas like air. As previously discussed, very young children (age three or even earlier; Piaget, 1930/2001) encounter the word "air," the word "wind," and the physical experiences of breathing and feeling the movement of air (e.g., wind, or air from a fan) in various contexts (including changes in air pressure). As children enter school, they interact with many of these ideas in new lights: breathing as a necessary component of life, ideas about photosynthesis and the conversion of carbon dioxide to oxygen, and ideas about weather and explanations for what causes wind. Entangled in the school-based conversations are the lurking everyday ideas about air, which are rarely the focal points of these activities. At what point do students have the opportunity to make sense of something so primary as air, which they have encountered in so many ways? When do they begin disaggregating the stores of ideas about air they have compiled over the course of their lives? With such ideas as fundamental as air (or water), students deserve opportunities to begin organizing and making sense of what air really is. The data presented here show that students have ideas about air, movement, and wind that while difficult to capture both verbally and on paper, are primary elements of how they make sense of a number of interactions with the physical world. As the results illustrate, students are capable of engaging with this process of disaggregation through the production of external representations.

Students initial statements about air focused on ideas about wind, breathing, and weather, yet a great deal of more sophisticated and complex ideas were incorporated into their explanations as they progressed through the interview sequence. The case study of Isis (Chapter 4) highlights the complexity of the ideas about air and particles that students' are capable of reasoning about. Through an iterative process of producing and refining both verbal utterances and drawings, Isis made significant progress in the first interview, as she began to unpack phrases about molecule spacing in different states of matter. On top of her statements about the relative motion of particles in gases and liquids, she was able to generate analogous ideas such as "flexible," which she used to describe air's compressibility. Ultimately, she appropriated a representation with which she was presented (i.e., the dots on paper drawing, see Figure 6.B) to describe differences in compressed and ambient air through the spacing of the molecules in these two conditions. In the animation session, Isis furthered her explanations by beginning to relate the ideas of "flexible" with differences in molecule spacing; she eventually reasoned that water is less "flexible" than air, because the molecules in water are closer together. Reasoning about complicated mechanisms to describe compression, about molecules and atomic spacing in different materials, and ultimately describing air's resistance to compression (molecules spread out because air "it needs to go around everything"), Isis demonstrated a complex array of ideas about air that she successfully navigated and appropriated to make sense of the linked syringes. While this is the case study of one particular student, the findings of such rich and generative ideas about air were not isolated to Isis alone; students‘ productions were comprised of a multifaceted collection of ideas about air that were rich, meaningful, and relatively sophisticated.

The literature on students' ideas about air, as mentioned, tends to measure their reasoning against canonical descriptions and models (Driver et al., 1994); very few students are considered to have an "adequate" understanding of air or the particle model before instruction (Lee et al., 1993). At first glance, the ideas offered by students in this study confirm the findings in the literature. However, building from their initial ideas of *space*, *movement*, and *strength* to explain the compression case (see Chapter 5), the substance of their reasoning evolved into more complex ideas that combined notions of quantity with ideas of process and mechanism. From reasoning about space and movement (see Chapter 5), many students developed a two-quantity model (see Figure 26) for compression. Students described each syringe as having a separate quantity of air, and when both quantities were pushed into the connecting tube, the amount of air was larger than the space inside the connecting tube (there is "too much" air; or as Kandice said, "It can't really fit in here"). The idea of "too much" was the foundation for descriptions of a linking process that explained why the plungers stop moving (effect) when being pressed simultaneously (cause). Furthermore, while many students struggled at first to describe a mechanism for the "push back" felt in the plungers, arguments concerning the quantity of air and available volume in the connecting tube lead many of them to the idea of “squished.” Explanations for compression as “too much” air “squished” into the connecting tube was an achievement for many students (e.g., Isis - Chapter 4; Norris - Chapter 6), as they could now focus on “squish” as an idea they needed to unpack and describe. For some, this description included the idea of “parts” of air (or even “molecules,” such as with Isis and Tasha) getting closer together and further apart. Narrowing descriptions of cause and effect with compression to the idea of “squish” resulted in many students going from simple descriptions of the causes and effects to articulating a linking process between the two. This shift, for many, was facilitated by a discrete representation of air, which provided a means for describing “squish” in terms of the arrangement of parts of air inside the syringes.

The use of a discrete representation as a tool or thought amplifier has powerful implications for how students make sense of compression in air. A focus on “squished” also decreased the dependence on the two quantity model for students (e.g., Isis), focusing their discussions on a single quantity of air being compressed (e.g., Kandice, Norris, Isis, Oscar, Oriana). Many students continued to speak about two plungers pushing air into the connecting tube, but quantities of air “meeting” in the middle was less of a focus by the third session. This may be due, in part, to the objects students selected to “stand for” air inside their physical representations. With Oscar, for example, his description of compression involved moving the ball bearings he selected as representations of air to the middle of the connecting tube in his device (see Figure 43). His explanations focused more on the arrangement of the ball bearings, than on the two-quantity model. However, it is plausible that the two-quantity model would still be useful to students in certain contexts, and this is a potential area of further study. Ultimately, students as young as 5th grade were capable of reasoning about mechanisms to explain what they observed in the linked syringes; the particular aspects of their reasoning appeared to relate to the particular representational tasks at hand.

2. Students, while challenged by the task of capturing an "unseen" on paper, are competent producers and critics of representations of air that capture the complexity and sophistication of their reasoning.

The task of capturing ideas about an unseen entity, such as air, on paper was challenging for students in this study. Similar to the process of young children slowly developing the capacity for representing their ideas (Piaget, 1936/1977; Piaget & Inhelder, 1966/1977), students are rightfully challenged by the task of generating external representations for that which they cannot see. The particular challenge was highlighted in the case study of Isis. Her drawing of air inside a container (see Figure 13) included a written label with the word "air," which she wrote, "just in case they [the viewer] didn't know." I interpret her inclusion of this label as an indication of her uncertainty with the task of creating an inscription or symbol for air itself. Similarly, Kandice (see Chapter 6) was challenged by the task of drawing air, as she said, "Because air is clear." Yet, despite the challenge, students successfully generated symbols for air (wavy lines in Kandice's case, lines and dots in Isis's case), which eventually objectified their ideas about air.

External representations (particularly the act of inventing and refining meaning) have an important duality that make them a valuable lens through which to analyze how students reason and develop understanding. The distinction is based on a duality captured in different ways by different theoretical frameworks (see Breidenbach, Dubinsky, Hawks, & Nichols, 1992; Douady, 1997; Ferreiro, 1994; Sfard, 1991; Tolchinsky-Landsmann & Karmiloff-Smith, 1992) between *process* and *object* (or tool, in Douady's [1997] terms). From one perspective, the operations or actions required to represent an idea can be considered as a process, method (Skemp, 1971), or a series of steps to follow. Sfard (1991) argued that (in mathematics) "the majority of ideas originated in processes rather than objects" (p. 11). Once produced, these representational artifacts (i.e., the symbols and inscriptions) become conceptual objects (or tools; Douady, 1997) in their own right (Olson, 1994), whereby the object, while being a representation, is perceived as the referential idea. This structural conception (Sfard, 1991) of representations allows the individual to reflect upon the idea as embodied in the external representation. Therefore, external representations can be both a process as well as conceptual objects. For students inventing or appropriating symbols and inscriptions for air, they are engaging in the *process* aspect of representation; laboring through how they will go about capturing an unseen in some visible form. However, once created, the symbols they produce can become conceptual objects in their own right, upon which they can reflect. Over the course of the interview sequence, Isis, Kandice, and all the other students gained comfort with both generating and appropriating symbols for air; they comfortably discussed these symbols as though they were air itself.

While Sfard (1991) emphasized *process* first and *object* later, I argue it is important to avoid this duality and instead propose the simultaneous existence of these two activities. Sfard (1991) used historical data to illustrate how process precedes objectification, however, this historical lens presumes a hierarchy that undervalues the potential interplay between process and object. The act of representing (i.e., the process) helps us to organize and refine our ideas (Kaput, 1991), and the artifact we generate (i.e., the object) becomes a vehicle for thought. Making one's implicit ideas explicit involves the process of generating an external representation that, in turn, yields an artifact on which the individual can act (Pozo et al., 2006). In the context of students' reasoning about air, the process and object characteristics of representation work in cooperation to support the construction and articulation of explanations.

The initial difficulty exhibited by students with the task of capturing air on paper illustrates the process aspect of representation. Once created, these symbols were appropriated in successive drawings to demonstrate ideas about air. As students explained their drawings, the symbols they created became a focal point in describing how air behaved in the syringes. Oscar (see Figure 28.A) first drew a dot in the middle of the connecting tube and used this to describe his idea of a "ball of pressure." Yet, in his next drawing, Oscar varied this symbol and the associated explanation (see Figure 28.B). He engaged in the process of changing his particular symbols to support shifts in his explanation (or perhaps he varied explanations to support new symbols), in what I consider to be evidence of simultaneous process and object use of representations.

Underlying the particular mechanics of object and process aspects of representation is the native competency of students to invent representations (diSessa, 2004; diSessa & Sherin, 2000). The capacity for invention relates, in part, to the process aspects of representation; students inventing are engaging in the process of creating a representation of some referent. However, recall the earlier discussion (see Chapter 2) regarding the use of the term "invention" as opposed to "production." It may not always be that students' symbols are true inventions (e.g., the use of a line does not mean the student invented lines). Regardless of whether the student invents the symbol or appropriates a symbol, that representation is a product of the student's creation and as such naturally becomes object once it is created; the student produced the representation employing the chosen symbol, and thus the symbol relates to the ideas the student intended. Furthermore, as Azevedo (2000) highlighted, students also have strong capacities for critiquing representations. This was evident in how the students in this study were able to critique the example representations with which they were presented. Interestingly, these students saw the examples as conceptual objects, referring to lines and dots as "air" in the examples, and they critiqued the quality of those symbols. I argue that their own productions (and challenges faced with "showing" an unseen) primed them to engage with a symbol as object, and allowed them to reason about the underlying science ideas captured in the examples. They had produced symbols themselves, and as such were able to see elements in the example representations (e.g., dots, lines) as symbols for air as well. The students understood that small dots in the example drawings and animations stood for air, and they were able to assess the quality of both the ideas being expressed (e.g., dots getting closer together in compression) *and* the particular symbols and inscriptions used to communicated those ideas.

Research Question 2: What are the relationships between students' productions in each of the representational forms and their understandings of air and the particle model?

3. Drawing helped students organize the elements of the linked syringe problem, to begin developing more specific and precise explanations.

The central thesis of David Olson's (1994) book *The World on Paper* is "how the very structure of knowledge was altered by attempts to represent the world on paper" (p. *xvii*). While this is a far more powerful idea than the intent of this dissertation, there is a similar sentiment in that statement to the role of drawing (and other representations) in students' reasoning about air in this study. As the students' drawings of compression illustrate, the act of putting ideas on paper appeared to help them structure and organize the problem of explaining the linked syringes. The first piece of evidence in support of this claim is students' invented symbols (or inscriptions) for compression at the mid-point of the connecting tube (see Figure 27). Regardless of the particular meaning of these symbols, their usage marked an effort on the part of the students to call attention to a point in the system that they deemed important. In a similar manner to how students use dummy numbers (Alvarado & Ferreiro, 2002; Brizuela, 2004) or dummy letters (Quinteros, 1997), these symbols marked points of interest that students went on to describe and reason about in detail. The ideas that students offered before producing a drawing included elements of space, movement, and strength; when explaining their drawings, students were able to begin combining ideas into composite explanations, offering more detailed descriptions of compression. For example, while creating his drawing of the pushing case in the syringes (see Figure 48), Norris introduced the idea of air as "people" being pushed from syringe to syringe. This alternative means for talking about air allowed him to be more detailed in his descriptions of how air moved in the syringes, and ultimately lead to his discussion of "crowded" people as an explanation for compression. Additional evidence of how drawing supported reasoning is the formalization of the two-quantity model of air in the syringes (described above), which many students discussed orally and included in their drawings (see Figure 26).

Before putting anything on paper, students described why the plungers stopped moving at a certain point when pressed simultaneously by evoking ideas of air moving out of the syringes into the connecting tube, too much air in the connecting tube, or evoking a strength comparison between the "push" from the plungers and the air in the system. They offered descriptions with little inclusion of underlying mechanisms that would account for the observed behavior. However, as students captured their thinking in drawn form, they more clearly articulated why the plungers stopped, including, for some, the introduction of independent quantities of air coming from each of the syringes. While this is clearly a non-normative explanation, it was more precise than earlier offerings. An argument could be made that this is not necessarily a positive development, as the two-quantity model may introduce "wrong" ideas about compression. In response, I would argue that organizing the problem through the production of a drawn representation resulting in the construction of a model for compression was an integral component of students later reasoning about mechanisms (e.g., "squished"). Clearly identifying the elements of the problem allowed students to begin locating areas of interest (e.g., the midpoint of the connecting tube, see Figure 27), which in turn increased the precision, detail, and efficiency of their explanations in furthering their reasoning about air. Placing ideas on paper is a relatively simple means for helping students organize a problem, and it has been shown to help students reason in mathematics (e.g., Brizuela, 1997) as well as science (e.g., Sherin, 2000). As Pérez Echeverría and Scheuer (2009) suggested, external representations “assist the explication of relations among pieces of knowledge” (p. 11). Furthermore, Pérez Echeverría and Scheuer (2009) argued that putting something on paper (or other forms) “‘illuminates’ the knowing relation, making it possible to represent not only aspects pertaining to the object, but also the ways whereby the knowing subject or learner has an access to such an object and relates to it” (p. 11). I contend that the evidence presented here confirms these prior reported ideas, that external representations organize thinking by placing ideas in an accessible form and revealing the relations between aspects of one’s understanding.

4. Animation facilitated students attending to specific points in the process of compression in the syringes to explain larger, observable changes.

The use of student-generated stop-motion animation was a novel element of the research design; only a few other studies have addressed students constructing animations of their thinking in the past (see Chang & Quintana, 2006; Chang, Scott, Quintana, & Krajcik, 2004; Church et al., 2007). As described in Chapter 3, the literature on the use of animation as a learning tool is in disagreement about the effectiveness of the medium (see Ainsworth, 2008; Morrison & Tversky, 2001; Tverysky et al., 2002). While some point toward their own research as evidence of the power of presenting students with animated representations of dynamic processes (Hagerty, 1992; Kaiser, Proffitt, Whelan, & Hecht, 1992; Mayer & Anderson, 1991, 1992), others suggest that the results are questionable and perhaps byproducts of specific methodologies (Morrison & Tversky, 2001). More recent literature on the subject begins to point to the particular advantage of discretizing complex dynamic processes (Ainsworth, 2008; Tversky, Heiser, Lozano, Mackenzie, & Morrison, 2007). The major difference between these contributions and the results of the present study lies in who holds the "reins" of production; prior research has focused on how students interpret animations, and this study allowed students to be the producers of these representations. I propose that students creating animations are breaking complicated ideas down into smaller changes in a static, frame-by-frame arrangement. This structure supports students' reasoning about change and their efforts to make sense of the accumulation of these changes to describe macroscopic observations.

Students created representations of their ideas about compression in animated form, which demonstrated their capacity for reasoning about the problem in a piece-wise manner. In other words, as Nicholas' case illustrates (see Figures 36-39), students constructing individual frames of their animation attended to the changes between points of time in the process under consideration. The medium itself, with its frame-by-frame structure, introduces time as an essential element of the representation. Representing points in time in the context of describing a process facilitated some students' spontaneous reasoning about change from instant to instant. Alternatively, for the students who did not spontaneously discuss changes from frame to frame, occurring over a smaller Δt

than the actual process, their explanations of these representations when viewed step-wise afforded them the opportunity to focus on *what* was changing. Deconstructing the animation into a series of static images that illustrate points of a process may have a structural advantage for reasoning about change over time when compared with continuous animations that are not discretized (Tversky et al., 2007). Additionally, after having generated their own animations of compression, students were able to critique an example (see Chapter 5) while paying attention to specific points in the process; their critique was pointed and precise. I hypothesize that there is an advantage to having produced an animation before interpreting one, however, further evidence is needed to explore the validity of this claim. To summarize, Tversky et al. (2007) stated clearly that, "The stubborn fact is that animations have yet to prove more effective than equivalent static graphics in teaching a wide range of topics" (p. 263). While claiming "proof" is irresponsible, I contend that the results of the present study suggest that a process of students generating animations may hold potential for supporting their efforts to make sense of change over time.

5. Building physical models challenged students to select representations of air, but afforded them the flexibility to modify their representations dynamically, and to the use of their constructions as explanatory aides.

Another relatively novel medium employed in this study was the construction of physical artifacts to serve as explanations (or explanatory aides) of students' thinking. Penner et al. (1997) established that students are capable of reasoning about mechanisms with devices they construct (which they call "models"). Building from this, students were offered a similar opportunity in this study[41]. The results presented here illustrate that selecting a physical object to stand for another physical object (e.g., ball bearings to stand for air) requires one to make explicit ideas a student has about the target (e.g., air). As was shown with Sarah, selecting a material to represent air moving in the linked syringes was met with uncertainty and reservation. Sarah overcame this challenge and selected a symbol for air (small pieces of Styrofoam) that she was comfortable using to describe her ideas about compression. Her original selection of metal ball bearings was done without complete satisfaction, because the "parts" model they represented did not align with her ideas about air. However, using the ball bearings as a placeholder, Sarah went on to find something "lighter" that the force of air coming from a pump could move more easily. Her willingness to work with different symbols for air ultimately facilitated her selection of something she was more satisfied with, and these symbols supported her efforts to articulate a mechanism for compression (i.e., spacing between these elements). Other students demonstrated a capacity for comparing their chosen physical symbols with their ideas about air as well. For example, Isis said that the ball bearings she selected

[41] The primary difference being that in Penner et al. (1997), students were building replicas of a human elbow, a mechanism that is directly perceivable. Students in this study were asked to build a model of air in the syringes, something they could not see.

were closer together than air molecules, and that they rolled, which was different from her ideas about how air molecules move (see Chapter 4). The structure of relating one material to another to make sense of and explain processes like compression relates to the literature on students' construction and use of analogies; perspectives on the use of analogy highlight why the process of cultivating physical representations holds potential as a tool to support reasoning.

The role of analogy in how students understand scientific phenomena has been heavily scrutinized (see Gentner, 1983; Gentner & Gentner, 1983; Clement 1987; Clement, Brown, & Zietsman, 1989). An analogy is generally a comparison between two elements on the basis of their structure for the purposes of explaining or comprehending one or both of the elements. In science education, a classic analogy employed by students is that electricity flows like water (see Gentner & Gentner, 1983). Gentner (1983) proposed the structure-mapping theory which posits that students generate analogies by searching a base domain (i.e., a domain with which the student is familiar) for elements that relate to the target domain (i.e., the idea in question); for example, the analogy of water flow to electricity is often used to describe how electrons may "flow" from the battery through the circuit like water flows down a stream. In this dissertation study, students considered different physical materials to represent air as a substance; the materials selected were analogous to air as a substance, and supported the explication of processes like compression. Generally speaking, students create analogies by mapping elements of the base domain (that they select) with elements of the target domain with the intent of making sense of the target through the ideas and structures from the base. Gentner (1989) suggested that these mappings tend to either be “superficially similar” (relating surface commonalities), or structurally similar (i.e., focusing on structural relationships that are deeper and more abstract than surface similarities). With the selection of physical objects, the relationship between base and target emulates these two aspects of analogy, superficial or structural similarity.

Some students chose ball bearings to show that air can push on things, which could be considered a superficial relationship; the base material (i.e., the ball bearings) was selected to indicate air’s (coming from a pump, typically) movement, rather than capture aspects of *how* air as a substance moves. Other students, however, chose discrete objects to illustrate a particular behavior of air itself, which I interpret as forming a structural relationship between the base (ball bearings) and the target (air). Within these structural analogies, the elements demonstrated the spacing of “parts” of air, or the movement of air from one point to another, thus emulating aspects of the material composition and behavior of air in the linked syringe system. In addition, those who intended their elements to “stand for” air were able to critique their selections relative to their ideas on structural, rather than purely superficial, bases: ball bearings were closer together than air molecules (Isis), they were heavier than air molecules, or the discrete nature was not like air, because air “is not formed by balls” (Sarah). The structural nature of their comparisons mirrors the structure of analogies; rather than elements standing as indicators, their inclusion in the students' artifacts served a deeper structural purpose. This was further evidenced by students' use of the ball bearings, for example, to describe particular cases of the linked syringe system (e.g., pushing, compression). In such instances, the elements were used to illustrate how air transmitted forces (e.g., with Kandice's corks as air), and how compression results in air molecules moving closer together (e.g., Norris' cotton balls as air; Isis's ball bearings as air). Therefore, I argue that students selecting physical elements to "stand for" something else generate analogous structures that can support reasoning.

Now, the selection of materials to stand for air by students in this study was not necessarily motivated by structural comparisons; students did not select ball bearings because they move like air. Yet, the selection and concurrent reasoning with the device as an explanatory aide (see Chapter 5) appeared to possess some of the same advantages as analogies in supporting student thinking. By focusing attention on the ways in which ball bearings moved inside the artifact the student built, for example, the student constructed a means for discussing air in the syringes. With Oscar, for example, the manipulation of his device was firmly integrated in his explanations of the various cases (i.e., pushing, compression). In similar ways that analogy provides individuals with means for making sense of that which they cannot see, the selection of a physical material to serve as a demonstration of air in the system supported students' efforts to make sense of processes like compression. Conceiving of physical constructions as analogies of other processes that aide the articulation of explanations deserves further exploration; undoubtedly, the structure of the relationship between base and target in this system is nuanced and likely different from the frameworks for analogies generated verbally that have received attention (Gentner, 1983). Regardless, the comparison between a constructed physical representation and analogies could serve to further our understandings of the usefulness and power of having students build their ideas.

Another dimension to this representational form that made it a powerful medium was the affordance of physical devices for real-time manipulation. In other words, students could use what they built to demonstrate, test, and refine their ideas and explanations for air in the syringes. Again, Oscar changed the configurations of his device (see Figure 43) to offer explanations for the compression case and the pulling case. By shifting the locations of the ball bearings, which stood for air, he was able to explain his reasoning through the device itself. Additionally, Kandice was able to demonstrate the pushing case using her construction (see Figure 59), while also contemplating the spacing between corks and whether a similar structure existed with air. Thus, she used her device to explain her reasoning, but the device, in turn, served to challenge her ideas and gave her pause as she considered the material composition of air. Analogies are typically used to aide explanations of particular phenomena, and the physical artifacts students constructed in this study served the same role.

Furthermore, the real-time manipulation of their devices provided students with opportunities to continue the development of their explanations for air.

6. Repeated representations in different forms allow for re-description, which supported students' reasoning about a mechanism to describe compression.

As reported in Chapter 5, the animation interview offered students an opportunity for representational re-description. The impetus for this re-description was partly due to the similarity between drawing and animation, in that animation can be a collection of drawings. All the students chose to use a white board and markers for their animations, making them an almost natural continuation of their drawing efforts from the first session. A majority of the students employed variations on their original symbols from the drawing session in their animations (see Figure 32, and Appendix C and Appendix D). That is, they shifted the symbols they used for air, presumably to fulfill some representational criteria they had generated, or because they had been presented with an example representation (e.g., dots on paper) that they preferred. For example, to further highlight the point at which two quantities of air met in the tube, Perry used intense shading of two different colors to represent two distinct quantities of air (see Figure 26). Isis shifted from using lines in the context of the syringes in the drawing session to using dots in her animation (see Chapter 4); as did James and Tasha (see Figure 35). Kandice shifted the orientation of her symbols (lines) to illustrate a difference between compressed and ambient air (see Figure 56). All told, the shifts in symbols, which were motivated at least in part by a desire to better explain compression, illustrates the process of "progressive symbolization" introduced by Enyedy (2005).

Recall the discussion regarding the associative bonds generated between ideas and representations (DeLoache, 1996; de Saussure, 1959). Students must construct links between their externalizations and their ideas. When they engage in re-representation, the "second generation" production - in this study, the construction of the animation - must undergo the same re-linking process described as "progressive symbolization" (Enyedy, 2005; Lehrer & Schauble, 2002). This is, with each successive attempt to represent an idea on paper, the link between referent and symbol must be reconstructed. These attempts to refine representations have associated effects on one's understanding (Enyedy, 2005). Alternatively, Karmiloff-Smith (1990) proposed "representational re-description" as a similar construct, where students undergo developmental changes whereby they represent elements of the same ideas in progressively more abstract ways over time.[42] Students regularly engage in such progressive symbolization or re-representational activities, which leads to increasingly complex understandings of the particular domain of study (Lehrer, Strom, & Confrey, 2002). An example from another discipline is the lengthy process of students coming to appropriate the conventional forms for writing numbers. Although they may begin to use the

[42] Karmiloff-Smith's (1990) representational re-description model is primarily concerned with internal representations; however, external notations play a role in the construction of such internal representations, thus this construct is relevant in the context of this study.

forms of written numbers from a very early age (around 3 years of age in most settings in which they are able to interact with these forms), students continue to struggle with understanding the nuances underlying the decimal place value written number system throughout elementary and middle school (see Fuson [1990] for a review of students' place-value understanding). This lengthy process is grounded in continual re-descriptions of the written forms to match students' understandings of number and the logic of the system. Inherent in this process of change is a pattern where students iteratively or cyclically produce and refine representations of understanding, and such refinement is heavily influenced by the ability of the child to re-construct a link between object and idea. As another example, students inventing methods for mapping height showed a progression from overhead representations to eventually creating and adopting topographical lines to represent changes in elevation (Enyedy, 2005). Similar to how students re-invent graphing (diSessa et al., 1991), each successive attempt to refine the representations resulted in complementary conceptual gains such that the new representations matched the understandings of the students. The process of representing and re-representing to refine knowledge (Waldrip, Prain, & Tytler, 2008) can serve as a thinking tool: our ideas becoming objects allows us to reflect on our representations, verify our thoughts, and contrast between different understandings and representations (diSessa et al., 1991; Kaput, 1991).

Students in this study demonstrated the ability to represent and re-represent their ideas between the drawing and animation sessions. Interestingly, these two representational forms share a common reliance on drawn symbols and inscriptions; re-description occurred within a particular type of representation. However, the third interview session required students to select a physical object to stand for air - pushing the boundaries of their representational criteria because whatever they selected was *not* air. Generating this link between a physical object and an unseen idea posed challenges for students, but leveraged the same ideas of progressive symbolization in terms of furthering thinking and reasoning. What transpired was a considerable shift where 11 of the 12 students selected a form of discrete representation for air, such as ball bearings, corks, or pieces of Styrofoam. This raises the question, what about the process of constructing a physical artifact to explain their ideas about the linked syringes in this particular study design led students to select discrete objects to "stand for" air?

Admittedly, the selection of discrete symbols for air in the final session could be purely a manifestation of the microgenetic design. Students were given a collection of materials from which to build their physical representations (see Appendix A for a list of materials), and perhaps that collection lent itself to the particular decisions students made. Unfortunately, I have no further evidence with which to argue this issue. However, some students explicitly stated that their selected materials were to show discrete aspects of air as a substance (e.g., Isis, Norris, Sarah, Tasha). If we consider a shift from a continuous representation on paper (e.g., lines and line segments) to a more discrete representation in the physical medium, interesting parallels can be drawn to the research on students' ideas about the particle model.

Students in upper elementary and middle schools tend to spontaneously focus on bulk, macroscopic properties of air and gases (Novick & Nussbaum, 1978; Pozo & Gómez Crespo, 2005) before being introduced to a particle model; findings which this study confirms, as well as the work of Piaget (1930/2001) and Séré (1982, 1986). Novick and Nussbaum, (1978) found that students in middle-school demonstrated a preference for the particle model when it is introduced to them, but they continue to reason with non-normative ideas about how particles are spaced and how they interact (Brook et al., 1984; Johnston, 1990; Novick & Nussbaum, 1978, 1981; Pozo & Gómez Crespo, 2005). Students adopt increasing numbers of ideas about the particle model as they age, and they have been shown to develop an understanding about a uniform particle distribution as they progress through grade levels (Novick & Nussbaum, 1981). Johnson (1998a, 1998b, 1998c; Papageorgiou & Johnson, 2005) presented a way of considering students' developmental progression with respect to a particle model that honors their attempts to make sense of the unseen and relatively abstract concept of air as particles.

Johnson (1995) worked with students ages 11-14 over three years in an interview study (that involved drawing tasks) which yielded four classifications of pupils' responses regarding the particle model of matter. These "models," as Johnson (1995; 1998a) calls them, progress from students conceiving of matter as a continuous substance (such as early drawings by Oriana, Wanda, and Perry), to variations where particles exist within some other substance (e.g., air particles are in air, as Tasha described), to an eventual model where particles *are* the substance, and their microscopic behavior describes observable macroscopic behaviors. While few students (Isis, Tasha, James) used the idea of molecules or particles in their descriptions of the linked-syringes, their chosen symbols for air shifted from more continuous to more discrete representations as they progressed through the interviews. Johnson described a similar shift over a considerable duration (years) as developmental; students understand the idea of matter as particles in a more comprehensive manner over time. However, as many have suggested (Brook et al., 1984; Johnston, 1990; Novick & Nussbaum, 1978, 1981), a particulate view of matter can be beneficial to students' reasoning regardless of the normative nature of the particular ideas. For some students in this study, the shift to thinking about air as a collection of small things - dots, ball bearings, Styrofoam - aided their reasoning about a mechanism to describe compression in air. This finding does not suggest that students understood the particle model in a canonical sense. Rather, it indicates the potential for "stepping stone" models (like "squished"), developed through a process of re-representation, as powerful tools for thinking and reasoning about mechanisms.

Contributions like Johnson's (1995, 1998a) models, and the other research presented here inform the design of studies and tasks for students engaging with the idea of the "atomic hypothesis" (Feynman, Leighton, & Sands, 1963). As

Papageorgiou and Johnson (2005) acknowledged, reasoning with elements of the particle model, regardless of accuracy or their normative nature, is beneficial to students' thinking about matter; students in this study benefited from representing air as a collection of small parts. However, as with Lee et al. (1993), many of the studies on students' ideas about air and the particle model consider students' ideas to be relatively static elements. In other words, emphasis has been placed on cataloging *conceptions* at particular ages, and measuring these conceptions against a normative model (such as with Lee et al., 1993); akin to the large body of work on students' "misconceptions" in science (e.g., McCloskey, 1983). Alternatively, I argue for a focus on the ways that students reason as dynamic processes (see Gupta, Hammer, & Redish, 2010), whereby ideas about air and particles shift, evolve, and change based on the context of exploration and the representations they produce. Yet, rather than an emphasis on developmental models (e.g., Johnson, 1998a) or conceptions of air and particles, further research should focus on the ways in which students use particle ideas (in a variety of accuracies) to reason and think about matter. In the cases presented here, students' selection of discrete representations of air supported their reasoning about possible mechanisms to describe compression. The ideas they used were by no means normative, yet they aided students' efforts to reason about linking processes between cause and effect. Furthermore, the ways students reasoned about different aspects of the syringes and how they introduced new ideas during the interview sequence (e.g., introducing analogies, such as with Isis and Norris) supports claims of student reasoning as a dynamical system (Gupta et al., 2010). The iterative process of invention and re-representation appears to support dynamic reasoning, and for the students in this study, invention and revision was a vehicle for students to think about “tiny things” (as Sarah said) of air getting closer together or further apart.

Questioning Research Question 2

The findings of this study point to an inconsistency in language between Research Question 2 and the evidence presented in this dissertation. The question asks, “What are the relationships between students’ productions in each of the representational forms and their understandings of air and the particle model?” While the question guided the design of the study, the findings suggest that particular use of the term “relationships” may be misleading. The question creates what may be a spurious separation between students’ productions and their understandings. In a sense, an emphasis on the “relationships” between representations and understandings suggests that understandings may exist independently of external representations. In other words, students’ “ideas” appear located in the mind and are not integrated with the representations they produce. The findings suggest a rather different structural relationship between ideas and representations. As the students demonstrated with all representational forms, their productions embodied their ideas, or their resources. Students constructed verbal explanations concurrently with their productions, and the interdependence suggests that considering students' understandings to be somehow separable from their representations is inconsistent with the data. Therefore, a focus on "relationships" between ideas and representations deserves further exploration as to avoid unnecessary (and unproductive) separations. Rather than consider "ideas" generally, further investigations should focus on how students construct explanations of the phenomena they encounter *through* the production of representations in different forms - verbal, drawn, animated, or built.

Research Question 3: How are students' understandings of air and the particle nature of matter impacted by representing these concepts across multiple forms?

7. Students traveled diverse trajectories over the course of generating multiple representations, which provided them with opportunities to express and refine their ideas in individually meaningful ways.

A major component of the design of this study was to provide students with the opportunity to become producers (or inventors) of representations of their thinking. I proposed that the importance of *production* can be derived from the nexus of three particular theoretical constructs (previously discussed): meta-representational competence (diSessa, 2004; diSessa & Sherin, 2000), process and object aspects of representation (Douady, 1997; Sfard, 1991), and the notion of progressive symbolization (Enyedy, 2005; Lehrer & Schauble, 2002) and representational re-description (Karmiloff-Smith, 1990, 1992). Amidst native competencies of invention (or perhaps more appropriately, production) and critique (diSessa, 2004; diSessa & Sherin, 2000), the interaction of the process of representing with the ideas objectified in the produced forms (Douady, 1997; Sfard, 1991) provides students' with autonomy to develop and express their thinking. Furthermore, production in a progressive or iterative sequence allows students to build on their prior ideas and representations. As the individual trajectories of Chapter 6 are reveal, when students have autonomy over the creation of their representations, they become engaged in the particular problems through creative control (Azevedo, 2006). Placing control over the design, form, and function of the particular representations in the hands of students[43] results in a diversity of pathways along which students developed explanations and representations of air in the linked syringes. As shown with Norris, Kandice, and Isis, similar ideas and relationships were present in their reasoning. These three students all captured ideas of air movement, aspects of quantity, and eventually an instantiation of the idea of "squished" at some point in the interviews. However, the particular symbols and relations between elements of their productions in each of their inscriptions bore little resemblance to one another; while ideas were similar, reasoning and representations were not. Additionally, the particular paths that each student traveled did not look the same, which is due, in part, to the representational freedoms that are afforded by invention. Interestingly, while each student used different ideas at different times to construct explanations, the

[43] As opposed to asking them to work with representations with which they are presented, like graphs or other mathematical notation.

similarity of some elements suggests a measure of convergence around ideas of air and compression. These students had certainly shared similar experiences with air: interacting with wind, breathing, and more immediately the linked syringes.

From a researcher's (and teacher's) perspective, perhaps the most interesting inference to draw from the diverse trajectories of students' representations and explanations is this: multiple representations across different media show us different aspects of what students know. As Wiser and Smith (2008) emphasized, students, even of the same schools and classrooms, start in many different places when it comes to thinking and reasoning about new ideas in science. In this study, students started in similar places, but the ideas expressed and captured in their representations were varied, complex, and they evolved over the course of the interviews; they introduced new ideas at different times, and they represented air in different ways. As researchers and teachers, we see very different facets of each student's understandings (as presented in Chapter 6), as well as the more generalizable trends of the group of participants (as presented in Chapter 5). This finding suggests that students producing multiple, varied representations of their ideas can provide the researcher and teacher a more complete (and possibly more accurate or nuanced) perspective of the patterns of reasoning and representational competency among students.

Furthermore, much of the emphasis on multiple representations in the science education literature has focused on students interactions with representations they are asked to observe (see Ainsworth, 2008b;[44] Gilbert, Reiner & Nakhleh, 2008). Clearly it is important to understand how students come to find meaning in the representations with which they are presented; however, a focus on how students *interpret* (Toth, 2000) or *comprehend* (Eskritt & Lee, 2007) representations fails to capture the richness of students' thinking. I argue that the production of representations is fundamentally different from how students interpret representations, and as such shows us, the teachers and researchers, different sides of students' thinking and reasoning. Additionally, placing the "reins" of representational production in students' hands allows them to direct their own sense making trajectories. For example, consider Norris' invention of the "people as air" framework. Inventing a context in which to reason afforded Norris freedom to talk about and represent air in whatever means he chose. He demonstrated complex ideas about compression and mechanisms for explaining the behavior of the syringes, all in a context of his own creation. The resources each student posses may be more fully realized when they become embodied in the representations they produce; the process of invention and revision both supported students' sense making efforts and, as mentioned, showed the teacher and researcher the richness of student thinking.

Research Question 4: How is students' reasoning about science influenced by the production and refinement of external representations?

[44] The literature on modeling (see Lehrer & Schauble, 2000; Schwartz & White, 2005) incorporates elements of students producing representations, but the explicit focus is not on multiple representations in this body of work.

8. Students' reasoning about compression evolved from unidimensional verbal explanations to more multidimensional explanations over the course of the interviews.

Within the microgenetic structure of the interview design, students' ideas about compression and their associated representations gained precision and coherence as they progressed through the sessions. Before discussing the particular aspects of this evolution, it is important to note that the evidence from this study cannot support or refute a claim that students' ideas became more sophisticated as a result of the interviews. Their explanations and descriptions gained detail and began to include descriptions of mechanisms for compression, however, the design of the study limits the degree to which we can assume a correlation between the particular tasks of this interview and the change in the substance of students' reasoning. Regardless, the evidence does suggest that over the three-interview sequence, students' ideas and representations of compression became more articulate and detailed. The particular concurrency of representational productions and thought is the focal point of this finding.

Students began describing the compression case (both why the plungers stopped and why the moved back out of the syringes when released) using unidimensional explanations that focused on *space, movement,* and *strength*. The ideas were unidimensional in the sense that each explanation or utterance tended to highlight one of these ideas, rather than attempting to combine multiple ideas.

For example, Nicholas began describing why the plungers stopped moving under compression by saying, “It’s impossible, because it’s stuck.” His explanation consisted of the idea of “stuck,” with little clarification of what “stuck” meant or why it occurred. These unidimensional ideas (i.e., space, movement, strength) were not mutually exclusive, however, and some students used more than one idea to describe different aspects of compression (such as using space to explain why the plungers stop, and strength to explain why the “bounce back”). Their reasoning tended to focus on one particular aspect at a time, until they began to put their ideas on paper. Drawing their ideas aided students’ efforts to organize aspects of the problem of compression, and to make explicit the particular points of interest in the linked syringes system (e.g., the middle of the connecting tube, described in more detail below; see Pérez Echeverría & Scheuer, 2009). By organizing and making explicit the components of the linked syringe problem, they were able to generate composite explanations, in which they formed relationships between certain elements of the compression case, such as describing a particular reason for why the plungers stopped at a certain point. For example, many of the students constructed a 2-quantity model of the air in the syringes wherein two distinguishable quantities of air, one from each syringe, “met” in the middle of the connecting tube and either could not pass either other, or filled the total volume of the tube. This model was used to describe compression, and the ways students used it in their explanations included ideas about space, movement, and strength. In a sense, this was the beginning of the students' efforts to articulate and reason about possible mechanisms that described the observed behaviors of the compression case. What followed was a process of co-constructing verbal explanations and representations. Efforts to refine verbal explanations were met with amendments or additions to representations (such as Isis's addition of arrows to highlight the movement of the plungers). In the second session, the students re-represented the problem, many of them altering the particular symbols they used for air, and they further explored the underlying processes that might explain compression. Taking a step back from the particulars of this study, the structure of this interaction between a representation and an idea is akin to how scientists negotiate meaning.

It can be argued that a scientific concept as we know it (e.g., gravity) does not exist without its accompanying representations. The scientific concepts that humans have agreed upon as the most accurate depend, in part, on the representations of these concepts, because these representations serve as the focal point for the negotiations that lead to accepted meaning. When a scientist proposes a new description of a phenomenon (such as Galileo's explanation of the acceleration of gravity and the proposal of distance traveled during uniform acceleration being proportional to the square of the elapsed time [Gribbin, 2002]), he or she captures this idea in some external form, which is used to communicate it with broader scientific community. For the domain expert (i.e., scientist), such a representation will likely include elements from conventional systems such as graphs or other accepted mathematical expressions. Once the idea is objectified in the representation, conversations regarding the validity, robustness, and accuracy of the proposed idea eventually decide the fate of the proposal. Discussions of newly introduced ideas center on the external representations that embody them, and eventually the community will come to either reject the idea or find shared-meaning in the representation - elevating the idea to a level of consensual knowledge (e.g., recall the previous discussion regarding the Feynman diagram; Kaput, 1991). We need to call attention to the inherent pattern existing within this negotiation of meaning (Confrey, 1991). For the community, the external representation helps to organize and refine a shared understanding, while each individual must reconstruct his or her associations between the representation and the underlying ideas. Therefore, the inherent pattern found in instances of meaning arriving from negotiation is present within the individual as well as within cultural contexts.

For the participants in this study, the microgenetic interview sequence created a context where each student engaged in negotiations with themselves and with me, the interviewer, around the substance of their ideas and the efficiency of their representations. Consider the case of Norris' animation. He created the animation in three distinct segments, first showing the pushing case, then the compression case, and finally the why the plungers "bounce back." With each successive addition, Norris reasoned about how he could demonstrate his thinking, and derived means for capturing his reasoning through our conversations. The discussions around how to show compression, leading to

Norris creating the idea of fans in his animation turning off as his representation of the air's resistance to being compressed, and the people "return[ing] to their space," illustrate this negotiation process. "Returning to their space" may have been an idea implicit in his description of "crowded" (see Figure 49), yet he did not verbalize the particular mechanism for why the plungers returned to their original position when released from compression in the first session. The act of generating the animation and reasoning verbally about how to demonstrate his ideas resulted in his creation of this explanation and the associated representation; Norris was concurrently developing inscriptions and explanations, in a process that mirrored the negotiation of meaning in which scientists engage. Representations and explanations are refined iteratively to better describe the particular phenomena in question, and Norris' construction of his animation mimicked that process.

More generally, the evidence from this study shows that repeated and refined representations are part and parcel of students' thinking and reasoning; students producing representations are negotiating meaning with themselves.[45] Through the production of representations, students are able to take intuitive ideas and further develop them into more coherent and robust explanations. For example, the general idea of "squished" used to describe the compression case by many of the students appeared to stem from intuitions about quantity and space.

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[45] This point is related to the above discussion questioning Research Question 2, challenging the distinction between ideas and external representations.

Students first described the "squish" case as the result of trying to push "too much air" into the connecting tube between the two syringes. I interpreted this description as related to everyday ideas about pushing, "squeezing" into small spaces, and students' observations that the total volume of the syringes was larger than the connecting tube (as evidenced by their descriptions of "too much" air for the connecting tube). Students are comfortable using everyday experiences as the basis for generating ideas (Hammer, 2004), and these experiences can be productive resources in making sense of science (Roseberry, et al. 2005). In this case, I interpret "squish" to be an everyday idea used to generate explanations of compression in the syringes. Kariotoglou, Psillos, and Vallasiades (1990) and Kariotoglou and Psillos (1993) studied early secondary students' ideas about pressure in liquids, and they proposed different "pressure models" held by the students. The simplest model (in their judgement) was the *packed crowd* where students anthropomorphized liquid to explain pressure differences in terms of crowdedness of the material elements; thus, the idea of "squish" as means for describing pressure has been reported elsewhere in the literature. In this study, working with this idea of "too much" resulted in students younger than those previously reported articulating descriptions of a mechanism that explained the "squish."

Sarah offered the following description in the final interview, "When you push both of them [compression case] in like that, it [air] gets stuck and they [things of air] don't have that much room cause they're like shoved in there [the connecting tube], that's why they're [the plungers] not moving. But if we spread out [release the plungers], they [the air] come back in [to the syringes].” She described compression in the prior animation session by saying, “It’s not that big [the connecting tube], it [the air] needs more room.” From what I consider to be an everyday idea that the air from the syringes was more than could fit in the connecting tube, Sarah generated this causal relationship between the amount of space in the tube and the amount of air coming from the syringes. In the next session, she began articulating a particular linking process, or mechanism, that described the causal relationship she had defined. Sarah did not mention the term molecules, and she actually resisted the selection of small, discrete representations for air. However, I argue that the mechanism she described was a useful “stepping stone” toward understanding compression in gases.

Lee et al. (1993) studied sixth-grade students’ ideas about matter and molecules, including students’ ideas about the compression of gases. According to Lee et al. (1993), “Prior to instruction, a very small number of students had an adequate understanding of scientific conceptions for compression of gases [as compared with after instruction]” (p. 262). They reported students in their study believed that air flows like water, and that it is unevenly distributed in a compressed system (e.g., a single syringe, in this case). One student described compressed air in a syringe by saying, “The air is all bunched up together. The plunger is pushing the air forward” (Lee et al., 1993, p. 261). Other students explained compression using particles and molecules, claiming they moved unevenly from one place to another. Lee et al. insinuate that these initial explanations were not “adequate” for describing compression, as though a single statement comprises the entirety of students’ ideas. A focus on adequacy assumes an idea is independent of a context, and that students’ ideas do not take on new meaning and usefulness in different contexts. Measuring ideas against some presumed adequacy raises the issue of whether the substance of students’ reasoning is considered static or dynamic.

I argue that students’ increasingly coherent and precise explanations and representations generated in this microgenetic interaction are evidence of the dynamic nature of students’ reasoning. With the case of Sarah, her intuitive ideas were refined through the process of representing her thinking and offering verbal explanations. In a sense, as she constructed externalizations of her thinking, she was able to refine her ideas and add more detail and precision to her explanations. Her ideas were not static, but rather evolved and changed within this short interaction to better explain her thinking about compression. Thus, I reject the characterization of students’ ideas as “accurate” or not, as Lee et al. (1993) promote. Instead, I offer evidence in support of students’ abilities to think and reason in evolving and developing ways, and I suggest that these abilities are more fully realized through the production and refinement of multiple representations.

9. While the literature on students' resources has discussed the role of context (Hammer et al., 2005), it has neglected to explore with any kind of depth the role of representational context (perhaps with the exception of Sherin, 2000), which the findings of this dissertation suggest can be crucial in how students make sense of science.

Following from the previous finding, and the proposal of a "manifold ontology of mind" (Hammer et al. 2005), the evidence from this study shows the importance of external representations in students' reasoning about science. One particular episode highlights this findings nicely, and that is Isis's adoption of the dots representation to show compression (see Figure 17).

Isis was asked to consider how the volume inside the syringes decreased in the compression case, and she suggested that it was because the air was being "compressed." When asked to elaborate on that notion of compressed, she paused and eventually said, "I don't know, it's hard to explain" (see Chapter 4, page 87-91). At this moment, I asked her to imagine a "zoomed in" version of the syringes, and Isis produced a descriptive gesture (see Figure 16) as she said, "[I] think it would look like all the molecules coming together." The combination of the specific question, her ideas about molecules, and her gesture all contributed to her articulation of a mechanism that elaborated on her idea of "compressed." Granted, this idea may have been available before this situation, and it likely was developed to some degree as evidenced by her use of the word compressed. However, re-framing the problem (i.e., "zoomed in") focused her attention on molecules, which in turn allowed her to reason (through her gesture) about a description of “compressed.” This episode also demonstrates the “manifold” (Hammer et al., 2005) nature of her ideas, as integrated with many forms of representation. Both her gesture (see Figure 16) and her verbalization were integral in the mechanism she described. Furthermore, the subsequent representation she produced involved newly appropriated representational elements. In her drawing of this idea of “compressed” (see Figure 17), Isis used dots as a symbol for air, which she encountered in the example drawing presented earlier (see Figure 6.B). She said she could show this ideas with dots, “kind of like how the fourth grader did” in reference to the example in Figure 6.B. Thus, her eventual drawing illustrated a complicated mechanism for describing compression (Figure 17), and it was an elaborate combination of her ideas, gestures, appropriated representations, and a particular context. As such, I argue that the “manifold ontology of mind” that Hammer et al. (2005) describe includes the external representations that students both produce and interpret. In other words, how we define context in terms of how students’ reason about science should now include, as a previously under-explored dimension, the external representations that students produce. In this study, the evidence of how students are able disaggregate their ideas about air with the spontaneous and generative production of representations in many forms emphasizes the centrality of external representations in thinking and reasoning.

Chapter 8. Conclusions and Implications

The findings discussed in Chapter 7 have implications for researchers, teachers, and the design of science explorations for students. In addition, this dissertation has raised numerous questions for future research and exploration. In this concluding chapter, I will summarize the findings and discussion as contributions to a theoretical perspective, detail implications for research and teaching, and discuss directions for future research based on the results of this work.

Contributions to Theoretical Perspectives

Perhaps the most salient outcome of this study was that while students' ideas about air are in flux, they are capable of reasoning in complex and sophisticated ways. At elementary ages, students have vast stores of resources for reasoning about the natural world (Hammer, 2004), and their task becomes building from these resources to create explanations of what they observe. Students expressed ideas about air's motion, air's relationship to weather and to humans breathing, air's resistance to compression, its ability to transmit forces, and other more subtle ideas about air as a substance. Each of these ideas were part and parcel of the representations they produced - either orally, in drawn form, in an animation, or in a physical construction; the variety of ideas embodied in representations exhibited in this study emphasizes the dynamic nature of students' reasoning. With an idea such as air, one with numerous "everyday" connotations, the production of multiple representations assists students' efforts to externalize these ideas in flux. At a basic level representations are tools for students to use in refining and developing increasingly coherent descriptions of their observations. The evolution of their ideas, which were inseparable from their representations in this study, suggest that multiple, repeated expressions can serve to improve the precision and quality of students' explanations. With a goal of science inquiry being students' pursuit of coherent explanations of mechanisms linking cause and effect (Chinn & Malhotra, 2002; Russ et al., 2008), the results of this study suggest that students' production of multiple representations should play a central role in inquiry. The externalization of ideas through various representational forms influences the very nature of those ideas, and significantly supports students' thinking and reasoning.

As was shown with drawing initially, the explication of ideas through the production of representations highlights the relations between aspects of knowledge. Inventing drawings, animation, or physical artifacts allows students to take whatever resources they poses and place them in a space for reflection and abstraction. As Enyedy (2005) eloquently suggested, representation is "the act of highlighting aspects of our experience and communicating them to others and ourselves" (p. 427). Generating a drawing or animation of one's thinking places ideas in an external space where they can be refined and improved. The discussion of *process* and *object* aspects of representation illuminates the power of not only learning to capture an idea in an external form, but the power of considering that representation as an objectified version of an idea that can be critiqued, tested, and developed. Layering many opportunities for reflection and revision through re-representation across multiple forms provides an opportunity for students to take everyday, intuitive ideas and to develop them into descriptions of mechanisms to explain cause and effect. The productions themselves become vehicles for assessing the quality and applicability of these mechanisms, furthering the pursuit of coherent explanations. At the heart of this argument is the primary contribution to the theory that this dissertation makes: students possess resources for making sense of the world, and external representations are embodiments of these resources.

A resources perspective is well documented and thoroughly discussed in the theory and literature on students' sense making in science (Hammer, 2004; Hammer et al., 2005; Roseberry et al., 2005; Warren et al., 2001). Vergnaud (1996) introduced the Theory of Conceptual Fields in which he describes "theorems-in-action." Theorems-in-action emphasize the importance of putting ideas in the external world - either orally, on paper, through gesture, or in some other form - for the purpose of working to refine and develop one's thinking. "In action" means exactly that, the ideas are actively engaged with and developed through their embodiment in some external form (i.e., representation). Similarly, Karmiloff-Smith and Inhelder (1974-75) promote the importance of children having theories[46] they can use to guide their interactions with the world. Vergnaud (1998) takes the importance of putting an idea "out there" for reflection and abstraction further by emphasizing the role of particular representations (from the mathematics perspective) as efficient means of developing understandings. Pulling from these two perspectives, the resources perspective, and the results of this dissertation, I propose that external representations are embodiments of the conceptual resources that students possess for making meaning in science. The vast stores of resources, gathered over extended periods of time interacting with the natural world, are what students use to reason dynamically about what they observe. As the results of this study show, external representations in the form of verbalizations, gestures, drawings, stop-motion animations, and the construction and manipulation of physical artifacts *are* the resources that students have for thinking and reasoning. I propose an expansion of the resources perspective to include a more explicit focus on the crucial dimension of externalizations in many forms. And, I call for continued research into how students spontaneously and productively use their multiple representations to develop coherent explanations. Furthermore, judging from the abilities of students in this study to describe and refine mechanisms for compression, external representations may broaden the scope of what we consider to be scientific inquiry, in where inquiry can be comprised of "putting an idea out there" in the form of a representation to test, critique, refine, and ultimately build into coherent explanations of mechanisms.

[46] They do not use theory in the same manner as Vosniadou (2002) or Gopnik, Meltzoff, and Kuhl (2001), who propose coherent theory-like organizations of ideas.

Ultimately, the results of this study confirm that multiple representations play a prominent and important role in how students learn science, and the findings posses numerous implications for teaching and future research.

Implications for Teaching

If we do not know the substance of students' ideas, we cannot help them develop and refine these ideas to be increasingly productive for explaining observations of the natural world; affording students multiple opportunities to express their understandings, across multiple forms, paints a more complete overall portrait of what students know. As for the particular forms of representation employed in this study, there are specific implications for classroom and instructional use:

- As was found with students' verbal explanations for the linked syringes, they are challenged by the task of generating verbal descriptions of complicated science ideas. Drawing organized students' thinking in this study by highlighting critical features of the problem toward which they could direct their attention. I conjecture that drawing may serve the same role in numerous science learning contexts. Providing students with opportunities to draw what they know not only informs the teacher of the student's ideas, but drawing also helps the students develop more precise and specific articulations of their understandings.

• Working in familiar systems of representation, such as with drawing, allows students opportunities for re-representation. A process of “progressive symbolization” (Enyedy, 2005; Lehrer & Schauble, 2002) affords students the use of their symbols and inscriptions as means for developing their thinking. As was shown with animations in this study, students are capable of refining their representations, and symbols, of a phenomenon to explore different, and possibly more generative explanations.

• The results suggest a unique quality of the stop-action animation medium that could be explored further in classroom settings. The episode of Nicholas highlighted (and Norris’ discussion of his animation as well) the frame-by-frame nature of animation, which parses larger-scale processes into small changes. With complicated ideas like gas dynamics, the affordance of the frame-by-frame structure provides students with opportunities to think about change over a small Δt; the accumulation of these small changes can support their reasoning about the larger processes that may pose problems for them. Extend this beyond gas dynamics to other, multifaceted dynamic processes and the power of the medium may help students think and reason about Δt.

• Students are rarely given the opportunity to build what they know; Bamberger (1991) emphasized the threat of constricting students’ expressive outlets. Students in this study not only demonstrated a capacity for building physical instantiations of their ideas, but also the ability to reason with these constructions as working models. In addition, the analogous relationship

> formed between their physical symbols for air and air itself facilitated their reasoning about structural aspects of air in the syringes. Thus, the opportunity to build working models may serve as powerful means for eliciting students' implicit ideas about topics like air, while giving them tools for further exploring their own understandings.

In science, students are all too often constrained by their knowledge of symbols and vocabulary. However, the constraints are relaxed when they are given the opportunities to use whatever resources they have to think and reason. Using multiple representations can facilitate students' reasoning with everyday ideas and intuitions to generate coherent and meaningful explanations. Furthermore, students must be given ample time to practice, refine, and discuss how they represent their ideas. Increased exposure to producing representations will likely hone students' communicative skills, provide them greater opportunities to become proficient users of representations, and eventually lead them to a greater appreciation of the conventional means of representation that have been developed over hundreds if not thousands of years.

A final note on the current popularity of standardized assessments (and perhaps more of a policy commentary than recommendation for teaching). As the results suggest, students have complex and dynamic ideas about the world. In this microgenetic study, deciphering the students' ideas and patterns of reasoning was a great challenge. The data were scrutinized during numerous conversations and written correspondences in order to tease out the patterns of student thinking and student representation presented in this dissertation. In a culture of schooling with increasing emphasis placed on symbolic knowledge (Bamberger, 1991), on standardized measures and testing (Ravitch, 2010), and a psychometric perspective of student "learning," the complexity, inventiveness, and adaptiveness of students reasoning becomes lost. Furthermore, without a focus on the richness of students' ideas, the assumptions of accuracy in large standard measurements are called into question. While statistical analyses may show reliability, and perhaps even validity, to what degree are we failing to capture the richness of students ideas and, as a result, making false claims about student achievement? Furthermore, to what degree are the results of these standardized measures leading to the design of instruction on false premises? Fostering what I consider to be students' natural abilities to generate and work with explanations for natural phenomena should be a focus of science education, not the unidimensional and static assessments of what students supposedly "know," which have dominated education conversations over the past decade (Ravitch, 2010). If many months of intense analysis of students' verbal, drawn, animated, and built representations of understanding is needed to unpack the complexity of their ideas (as was the case in this study), then it does not stand to reason that an assessment offered in a single setting in a single representational form can accurately capture the substance of students' thinking.

Study Limitations

The design of this study imposed some limitations that I would like to address. First, the microgenetic design created a particular context within which students offered explanations and descriptions of their thinking. Thus, how does one gauge the authenticity of the link between representation and understandings in this study as independent of the interview context? Much of what children do from a young age is playful manipulation of symbols and signs; a banana as a phone helps the child understand representation. Likewise, a student talking about people as an analogy for air may be playful, but also aides his attempts to represent the natural world in a manner that can be acted upon (e.g., critiqued, revised, explained verbally). While the responses by some students may appear like momentary ideas or even fanciful inventions, "messing about" is a beautiful way for students to learn how different ideas, models, tools, and representations, are all resources for formulating and articulating opinions and claims. Thus, the interviews may have generated a particular context, but we can learn from students' performance to begin thinking about more situated contexts, such as classroom settings. The findings present a foundation from which to design studies of multiple representations in social and situated environments.

Another clear limitation of the study was the relatively small number of participants. As the intent was to explore students' multiple representations of an "unseen," the goal was met and the research questions were adequately addressed. However, these findings are merely a starting point to begin exploring how students construct and use representations of different topics in science. The emphasis placed on symbolic knowledge increases as students progress through school, to the point where college science majors engage almost exclusively with conventional systems (e.g., mathematical models of phenomena), and rarely engage with idiosyncratic and invented representations. Thus, while the present study was limited to elementary students, the underlying tenets of the research have potential in the exploration of how older students reason and think with invented representations.

Finally, a comment about the particular models, representations, and ideas put forth by students in this study. Many of the ideas they captured in their productions and in verbal utterances were comprised of non-normative ideas and “misconceptions” (McCloskey, 1983). I acknowledge the potential for interactions such as this to reinforce students’ intuitive ideas that may not be productive. The intent of the study was to explore these ideas as opposed to specifically targeting a form of conceptual change. However, the data presented do not allow for conjectures about how students may develop more normative models (or the particle model, for example); this is an area of future study. Regardless, the goals of the study were met and the limitations mentioned here primarily serve to fuel future research endeavors.

Implications for Future Research

The findings of this study hold a number of implications for future research, both from a methodological stance and from a theoretical stance. I will take up issues of methodology, followed by questions for future theoretical and empirical consideration.

Methodological implications

As was alluded to in the discussion chapter, providing students with opportunities to generate multiple representations of their ideas gives the researcher different lenses through which to analyze their thinking. Within this multi-representational structure, researchers can more thoroughly explore students native representational competencies (i.e., an extension of diSessa's (2004) MRC), as new access points to the complexity of students' ideas. While conventional representations are clearly important, researchers can further explore and describe students' representational practices by allowing them to invent and refine in unconventional and idiosyncratic forms.

Freedom to explore thinking through the production of multiple representations also presents an opportunity for research on learning progressions. While learning progressions are idealized sequences, a thrust of the research in this body of work focuses on the individual trajectories that students take (Wiser, et al., 2009) while engaging with activities of the progression. Providing students with increased opportunities to produce and refine representations allows for a more complete diagnosis of students' ideas; multiple representations could improve our understanding of how students progress toward specific scientific models, such as the particle model of matter.

Finally, Schauble, Klopfer, and Raghaven (1991) described students' "outcome oriented" and "explanation oriented" models of experimentation. That is, in an "engineering" context, students seek to optimize some outcome, and in a more scientific context students seek to explain processes that link cause and effect (Schauble et al., 1991). As was shown with the various forms of representation here, students are capable of both "outcome" and "explanation" oriented models depending on what they are drawing, animating, or building. Students (generally speaking) described mechanisms to explain compression in their animations, and their physical construction served as working models. Thus, a multi-representational approach could provide researchers with insights into students' goals (outcomes or explanations of cause and effect) as they engage in sense-making activities. It is unlikely that students they take a single approach in all contexts, and multiple representations provides an opportunity to further explore models of student experimentation and exploration.

Questions for future research

As with any study, the findings uncover future questions that are too numerous to list. This section focuses on some of the most pressing questions for future investigation. First, the evidence presented in this study is comprised of representations and verbal utterances. What remains unknown is whether ideas and models are formed by efforts to produce external representations, or whether the representations are articulations of the models and ideas that students already posses. To some degree, creating a spurious separation by supposing a hierarchy (i.e., representation before idea or idea before representation) is unproductive, as the discussion regarding Research Question 2 suggested (see Chapter 7). However, future research is warranted to better articulate the idea of resources embodied in representations to explain how externalizing ideas in science influences one's understanding. Additionally, the introduction of social interactions, such as classroom settings, may further illuminate the nuance of the relationships between students' representations and their understandings.

Another finding worthy of future investigation is the diverse representational trajectories each student demonstrated over the course of three interviews. While being unique and idiosyncratic in many ways, the students' representations and ideas had surprisingly similar elements. That is, while students traveled different paths, there was convergence amongst some of their ideas, such as the idea of "squished" to describe compression. This convergence deserves further attention, and it deserves comparisons with historical accounts of representing unseens and understanding gas dynamics (see Piaget & Garcia, 1989). Related to this unexpected convergence is the particular affordances of each form of representation employed in this study. What about drawing, animation, and building physical models is unique and can, thus, but exploited to aide students' efforts to reason about mechanisms? While some patterns emerged in the ways in which students used each form to express and refine their explanations (e.g., re-representation in animation), the study design did not allow for a direct exploration of affordances; varying the order of production and other parameters would allow for an analysis of each form's independent contributions to thinking and reasoning.

Turning to a particular form of representation, future research into the stop-motion animation medium is warranted. In this study, students were capable of representing motions using animation that were smooth and fluid; they used Δt to explore the processes of compression, for example. If the medium lends itself to explorations of Δt, can this feature become a means for students to reason about more complex changes over time? In other words, does breaking down a process into frame-by-frame changes provide students with a unique opportunity to attend to small changes that can be accumulated to describe larger, perhaps more observable, processes of change? Considering the goal of science inquiry is to promote students' pursuits of coherent explanations of mechanisms, perhaps the structure of the animated medium is a platform for students to produce and refine representations of mechanism, and thus generate more coherent and productive explanations.

Finally, further investigation into the analogous relationships between ideas and representations generated in the physical construction task may prove beneficial to teaching and learning activities. As Bamberger (1991) said, "Students who are most successful, even virtuosos, at using their hands to build and fix complicated things in the everyday world around them are often the same students who are having the most difficulties learning in school" (p. 38). Leveraging the practice of building ideas to support students' thinking requires future work to further articulate the relationships between what students build and their developing ideas about scientific phenomena. If students begin to better understand representational practices through these unconventional forms, perhaps we can use these alternative media to support students' developing understandings of more conventional systems. Students producing representations can engage in assessments of the quality of those representations *and* the quality of their ideas, which is an essential practice of science itself. Therefore, external representations need to be an explicit focus in future science education endeavors.

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Appendix A. List of materials for physical construction interview task.

The following is a list of the materials made available to the students for construction of their physical representations of air and the linked syringes.

- Cardboard (thin solid stock, thick solid stock, corrugated stock)
- Styrofoam plates
- Index cards (3x5", 5x8")
- Balsa wood (assorted sizes)
- Wooden dowels
- Clear PVC tubes, various diameters
- Popsicle sticks
- Masking tape
- Duct tape
- Adhesives (glue, glue gun, quick-drying epoxy)
- Binder clips
- Clothes pins
- Velcro
- Springs (assorted)
- Straws
- Cork stoppers
- Paperclips
- Plastic spoons, knives, forks
- String
- Marbles
- Cotton Balls
- Cotton stuffing
- Balloons
- Rubber bands (thick and thin)
- BBs, small ball bearings
- Paper cups
- Sports ball pump
- Balloon pump
- Plastic tubing, various diameters
- Zip ties

Appendix B. Description of SAM Animation educational software.

SAM Animation (Searl, Gravel, & Rogers, 2011) is easy-to-use stop-motion software developed specifically for students and teachers. The software interface (see Figure 1) centers on a live video stream from a USB webcam from which the user “snaps” still images that become frames in the animation. Students generate animations by manipulating everyday craft materials - construction paper, clay, fabrics, markers and white boards - while capturing individual frames that are placed in a timeline. In essence, students make a digital version of a flip-book, where static pictures of tactile materials are combined and played back at a prescribed rate to convey motion. Students combine idiosyncratic representations as well as elements of conventional representations (letters, numbers, arrows, etc.) in their animations to dynamically express scientific processes.

The SAM Animation environment is powerful for multiple reasons. First, students are familiar with drawing and craft materials and, thus, the content of each animation involves familiar media. Second, the software itself was constructed using extensive classroom testing and iterative, participatory design. Prototypes of SAM Animation have been in classrooms for over five years where opinions from teachers and students about features, usability, and overall approaches to animation informed successive iterations of the product. The result is software that is designed specifically for teachers and students in classroom contexts.

Finally, one of the central design tenets for SAM Animation was to focus students' attention away from the computer screen. The most powerful technologies facilitate interactions between students and ideas, while minimizing the role of manipulating the technology itself. In SAM Animation, students are focused on making their animations by moving physical elements on the table, and the software facilitates taking those tactile interactions and turning them into a dynamic representation of some process or story. SAM Animation is offered as a free download from (www.samanimation.com), and has currently been downloaded by more than 30,000 individuals worldwide. The ease-of-use and the focus on using familiar materials make SAM Animation an ideal tool for elementary school students' engagements with animation.

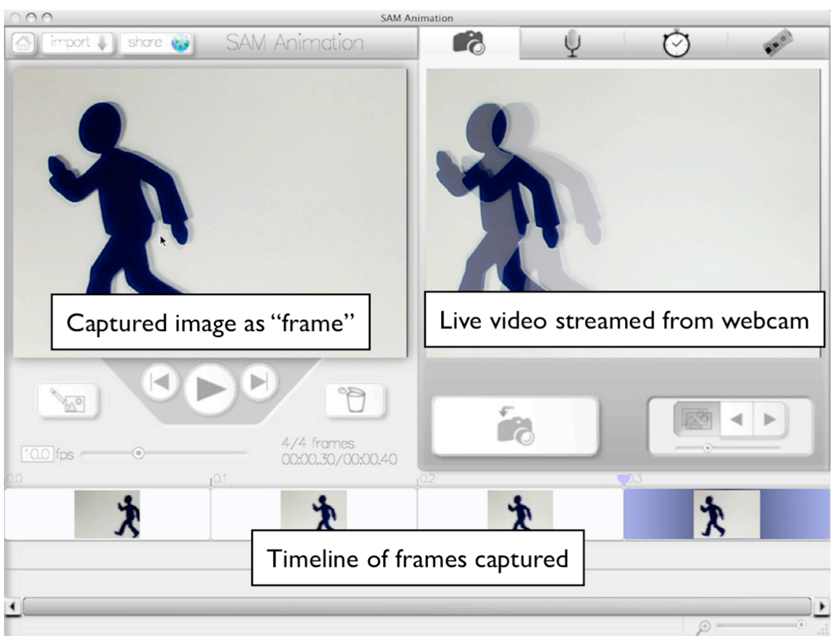


Figure 1. Screenshot of SAM Animation software showing live video image from webcam (right), captured image as a "frame" (left), and the timeline of images captured as frames (bottom).

Appendix C: Numerical indicators of compression findings

The table below lists the numerical indicators of specific trends in the data across all twelve study participants. These data are presented as a brief snapshot of the relative frequency of certain occurrences in the interview sequence.

8 of 12	students...	predicted the syringe plungers would not move in compression case.
4 of 12	students...	predicted the plungers would move in compression case (3 students quantified their predictions, 1 student did not).
10 of 12	students...	did not explicitly reason about cause and effect or a mechanism to describe the "push back" case.
9 of 12	students...	drew the pushing case first.
7 of 12	students...	drew a "two-quantity" model of air and the compression case, where a separate quantity of air was believed to exist in each syringe.
8 of 12	students...	revised or changed their symbols for air from the drawing session to the animation session.
6 of 12	students...	used discrete symbols as representations of air in their animations.
9 of 12	students...	approved of the example animation (Figure 8 - Example B) showing a particle "squishing" model of compression.
11 of 12	students...	selected discrete objects to show air in their physical constructions.
5 of 12	students...	built dynamic, exploratory devices the provided for them to explore their ideas through their productions.

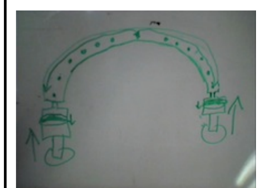
Appendix D. Table of students ideas, symbols, verbal explanations, and representations of compression (from Chapter 5)

See below

Appendix D: Table of students' ideas, symbols, verbal explanations, and representations of compression

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Isis</td><td>Air: lines; dots

Compression: blank space; dots spacing</td><td></td><td>Air: dots

Compression: dots meeting in middle; symbol at midpoint of connecting tube</td><td></td><td>Air: ball bearings

Compression: spacing of ball bearings inside model</td><td></td></tr>
<tr><td colspan="2">"All the air doesn't fit in it"; "Like, there's too many"

"Just like pressing all this air into something that won't be able to fit it."

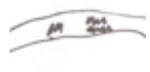
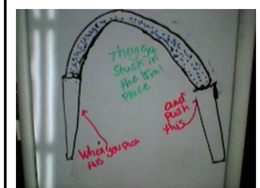
"It would look like all the molecules coming together"</td><td colspan="2">"All the air gets too tight in the middle"; "it's more flexible than a liquid"

"it's [air molecules] all coming close and close and close together"

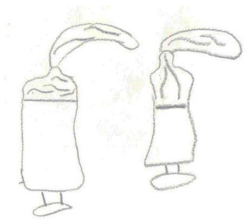
"water is not as flexible as air, because all the molecules are closer together"</td><td colspan="2">"They [ball bearings as air molecules] all get really close, and they [molecules] don't really like being that close in a gas, so they have to, like, release so they ll have room. And so that's why they push back down."

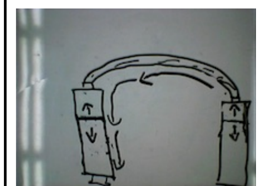
"...it's flexible because all the air molecules have their own space"

"We're getting it [air molecules] all together, putting all the molecules really close"</td></tr>
</table>

Student	Drawing		Animation		Physical Artifact	
James	Air: short scribbled lines Compression: lines in middle of connecting tube		Air: dots Compression: concentration of dots; text labels		Air: ball bearings Compression: ball bearings pushing out of syringe	
	"They would get, like, stuck" "Air is kind of moving around"; "gets stuck in the middle"		"they're [air] stuck" "The air is like right here [in the tube], getting stuck...cause there's too much [air], I think. And...when this air is [from opposite syringe] over here, doing the same thing"		(imagining two of his devices facing each other like the linked syringes) "The balls [bearings] probably would like stay at each other [stuck in the middle], or cross each other...you could probably put the straws on different sides [parallel between pumps] and they could [gestures his hands moving passed each other]"	

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Kandice</td><td>Air: lines

Compression: orientation of lines to show more air in compression</td><td></td><td>Air: line segments

Compression: arrows showing forces on plungers</td><td></td><td>Air: corks

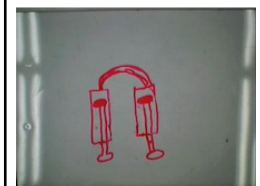
Compression: corks tightly packed in PVC tube</td><td></td></tr>
<tr><td colspan="2">“It’s not enough space for all the air”

“This is the one where you push it and most of the air, cause I put more waves here [left], and most of the air is, like, everywhere. And when it’s no so...pushed...there’s less air everywhere”</td><td colspan="2">“The air, it has a sort of strength.”; “it can’t really fit in here [connecting tube]”

(critique) “at first they separate [molecules farther apart], but then the close [molecules]”

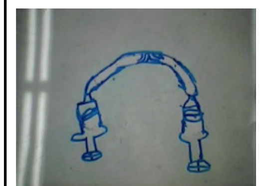
“because air is...let's see...air is, like, you can't really see it and it's not really like anything. So you're able to push it. Unlike water, water is like, something, a liquid...and you can see, and you can't really push it...in.”</td><td colspan="2">“When you push this one [linked syringes] you don’t see air moving, but if you push one of that [her model] you can see which way the air [corks] moved.”

“There's space in between them [the corks in her model]. But in the air I don't think so...not a lot.”</td></tr>
</table>

Student	Drawing		Animation		Physical Artifact	
Kendra	Air: line Compression: continuous line through connecting tube		Air: lines Compression: lines meeting in middle, blank space at the center point		Air: ball bearings Compression: ball bearings pushing out of syringe	
	"There's not enough strength to push it in" "...air goes through that [syringe] and the air comes through that [opposite syringe] and there's just the air stuck in the middle [connection tube]" (air resisting compression) "Some people need space, like the air needs"		"The air is pushing it back"; "two different parts" (air resisting compression) "it [air] falls back that way [into one syringe], and fall back that way [into the other syringe]" "Maybe air is like a line cause, like I said, air is kind of like wind"		"I mean they [plungers] can't move forward, cause it's [compressed air] just pushing them back." "...because when you're pushing [the plungers], air goes in [to the connecting tube] and it pushes back [the plungers] after"	

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Nicholas</td><td>Air: line segments

Compression: lines in middle of connecting tube; symbol with arrows</td><td>
</td><td>Air: line segments

Compression: lines meet in middle, new symbol to show point where they meet.</td><td></td><td>Air: ball bearings

Compression: ball bearings pushed out of syringe, second device showing air takes up space</td><td></td></tr>
<tr><td colspan="2">“It’s impossible because it’s stuck”

“Kind of squishy”; “I went in this car with my cousin, but it was too squished together and we can’t go any further until we get out the car”

“The air is pushing together, so that’s what this means [arrow symbol]”; “air is going all the way right here [middle], and they’re stuck”</td><td colspan="2">“...they’re almost there, like close to each other, and this is the part where it can’t go any further [shown by symbol in middle of tube], and that’s why it’s stuck right there.”

“the air gets squished together when you’re pushing both of them together, so they’re stuck”

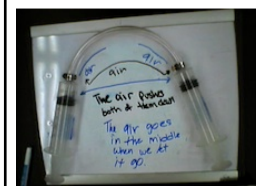
(critique) “how...the...air was getting stuck together...it gets squished together”</td><td colspan="2">“We're still pushing the air [out of the pump]. Like, the air is pushing the marbles straight to here [end of tube]. If I push, the air is pushing the marbles.”

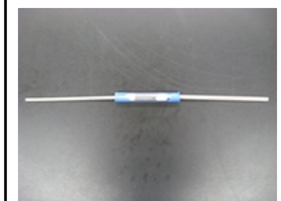
(pointing out difference between syringes, and his single pump device) “The difference is you need, you, for this one [his artifact] you don't need [a second pump]....But for this one [linked syringes], you have to use this one to push it back and forth.”</td></tr>
</table>

Student	Drawing		Animation		Physical Artifact	
Norris	Air: lines Compression: vertical line in the middle of the connecting tube		Air: lines; people Compression: people pushed together, move apart when not pushed		Air: cotton balls Compression: two pumps pushing cotton balls together	
	“They get pushed out [of one syringe into the connecting tube] and it’s crowded in here [in the connecting tube]. And then they get pushed out at the same time, but it’s crowded in here [in the connecting tube]. They won’t have a place to go, cause it’s filled, and they won’t have a place to go cause this is filled.”		(why plungers stop) “they’re pushing it both together, and they go to the middle....” “If we push both of them [plungers] at the same time, they’ll [the people] all go to the same place and they will get stuck”		(device description) “It's like the syringe when, so, if they're spread out, see? Spread out...it's like, like I said...it's pushing them [cotton balls] all together”	

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Oriana</td><td>Air: shading

Compression: shading throughout connecting tube</td><td></td><td>Air: none

Compression: labels for air coming from both syringes; focus on air resisting compression</td><td>
</td><td>Air: ball bearings

Compression: spacing of ball bearings inside model</td><td></td></tr>
<tr><td colspan="2">“Because there’s like air in both [syringes, being pushed into tube] of them so it can’t go up”

(air resisting compression) “Since a force is not pushing air one way, it’s just pushing both of them down”

“The air is pushing them back down”; “because it’s a lot of air”

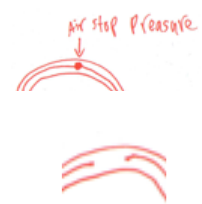
“Air’s like stuck in the middle”</td><td colspan="2">(air resisting compression) “when we let them go, the air just went back like equally in both of them [syringes]”

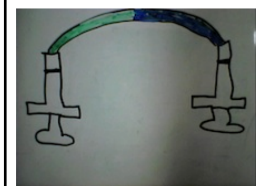
“it’s just both of them equally pushing the air up”

“when we push both of them [plungers] up, the air is, like, getting bigger inside the tube”</td><td colspan="2">“This, the white one [cotton ball plunger in her model] pushes on the next one [air as ball bearings] so it pushes all of them.”

“...the syringes are, when you push both of them, the air pushes like both of them down [air resisting compression]. And when you do this one [her model], when you push both of them it just doesn’t go”

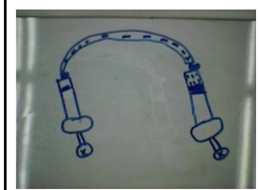
“This is [ball bearings] can be pretend as like the air...”</td></tr>
</table>

Student	Drawing		Animation		Physical Artifact	
Oscar	Air: lines Compression: symbol at midpoint of syringe; blank space		Air: shading (blue) Compression: shading throughout the connecting tube		Air: ball bearings Compression: ball bearings in middle of connecting tube	
	"the air's like right there [middle] so it had like a certain amount" "I put the ball [symbol] to say that both airs are just going to go like sssshhhh together [gestures hands coming together]" "You can't see nothing...but you know there's gonna be a gap"		"You see that they just get pressured" (air resisting compression) "when you're doing the pressure, it's just like, when you let go, the pressure is just pushing that, the thing, the stoppers" "...it would look different [when we're not pressing]"		"Cause, like, you're just putting it [air as ball bearings] all in the middle [connecting tube]...and it's not doing anything. It's just like the air...it's like a big gap." "it's [air] all squished [under compression]" "when you're like pressuring it [the air in the syringes]...the pressure gets stronger, and stronger, and stronger, and then when you let go...[demonstrates ball bearings moving back into the cups in his model"	

Student	Drawing		Animation		Physical Artifact	
Perry	Air: lines, two colors Compression: two colored concentrated scribbles		Air: shading Compression: two colors, one filing each half of the connecting tube		Air: ball bearings Compression: air pushing ball bearings	
	"The air doesn't have no where to go" "the air comes from there [one syringe], the air comes from there [opposite syringe] and it's all stuck all here [draws scribbles in middle of tube]" "they all get stuck right here [middle] cause they have not where to go...they're all forced together, like a bit wall"		"it's a lot of air"; "there's a lot of air in there [connecting tube]" "there's too much air" "both of them [two airs] are struck right here [middle of tube], that's why it's so hard [to push the plungers]" "both stuck right here [middle], they can't go anywhere"		"it's not enough air [from the pump] cause it's a little tube [the straw]" "it's not strong" **Focused on air from pump moving ball bearings to show "how air pushes"	

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Sarah</td><td>Air: long line segments

Compression: line segments throughout connecting tube</td><td></td><td>Air: short line segments

Compression: line segments throughout connecting tube</td><td></td><td>Air: styrofoam pieces

Compression: spacing between sytrofoam pieces</td><td></td></tr>
<tr><td colspan="2">“...that one [syringe] is pushing into that one [tube], but that one at the same time is pushing into that one [tube]. So, it’s hard to...the air is too strong, and it can’t push”

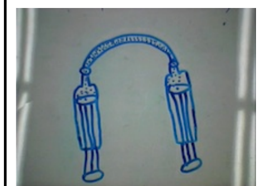
“The air is going through, and then it gets heavier, and then it stops”

“It wants to go in that one [syringe], it might want to go in that one [opposite syringe] so it doesn’t know, that’s why it’s stopping in the middle”</td><td colspan="2">“Both of them [plungers] are being pushed in, but they’re getting stuck”

“the air is in both of them [syringes] and in the middle [connecting tube]”

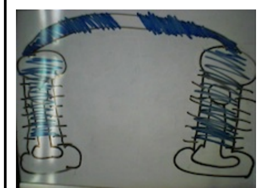
“all of the little, like, all of the, um, little things of air are being, are like squished in there and they can’t move or anything. And then after when you, um, let go [of the plungers], they [air] push back through [into syringes”</td><td colspan="2">“[air as styrofoam pieces are] close together [under compression]”

“Um...because air...is formed, not formed by balls. It's formed [by] tiny little things, it's formed by these [styrofoam]...and, because when you push both of them in, air, when you push both of them in like that, it [air] gets stuck and they don't have that much room cause they're like shoved in there, that's why they're not moving. But if we spread out, they come back in [the syringes].”</td></tr>
</table>

Student	Drawing	Animation	Physical Artifact
Tasha	Air: line segments Compression: line segments throughout tube 	Air: dots Compression: higher concentration of dots 	Air: ball bearings Compression: tighter packing of balls in secondary demo (bottom) 
	“The air gets stuck...half of the air from the other tube and half of the air from the other tube goes in [middle], but the rest gets stuck in the middle” “there’s not enough room for all the air to go in” “when it’s squeezing [compression case], it’s squeezing, the air is changing because when, when you have both of them in the same place it [air] changes while you’re moving it [plungers]”	“ [the dots are] molecules that’s floating in the air” “I’m showing when...the first part is when they have more molecules in the [syringes]...and then after that, the second try, there’s more, the plungers is pushing out more tu, ah, more molecules inside the [connecting tube]” “There’s too much molecules, and they’re smushed up together, and there’s no more room”	“Um, when the air and the molecules push together, and it gets stuck in one tube, there’s too many in one tube to push the other side.” “it’s because the molecules in the air are pushing, are pushing the plungers down because there’s too many, there’s too many molecules [in the connecting tube]” “they’re closer [ball bearings as air], when they’re pushed together it’s [air] closer together, and there’s more molecules”

<table>
<tr><th>Student</th><th colspan="2">Drawing</th><th colspan="2">Animation</th><th colspan="2">Physical Artifact</th></tr>
<tr><td rowspan="2">Wanda</td><td>Air: shading

Compression: blank space (“gap”)</td><td></td><td>Air: shading

Compression: blank space (“gap”)</td><td></td><td>Air: none

Compression: syringe in middle of tube extends when two pumps are pressed.</td><td></td></tr>
<tr><td colspan="2">“Well, it was hard to push it up and, like, there was still more air [in the syringes].”

“it [air] can’t go to both sides”; “cause if you’re pushing it [the plungers] up like this, it [the air] won’t go to both sides, and it’s really hard.”

“the air is forcing it to like not be strong enough to push all the way up here.”

(air resisting compression) “because of the air inside [the connecting tube].”</td><td colspan="2">“...[the air], it gives up, so like, it's forcing, the air is forcing to push this thing [plungers] back down so the air can stick inside [the syringes].”

“...it's like saying it's trying to pop [compressed air] it, but it can't, so it [the air] just gives up and pushes [the plungers] back down. “

(critique) “The dots are...the dots are getting together”;
(critique) “...the same way that I explained it.”</td><td colspan="2">“When we push the two airs up, the air, like is inside here and then it’s getting ready to go...come out. But, it couldn’t, cause it’s like another tube [opposite syringe], so the air’s coming out from this. And same from that.”

(device description) “The rest of the air is coming together [in the connecting tube]...the big force of the air shoots out the [plunger]”</td></tr>
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