Making “unseens” visible: Multiple representations of students’ understandings of air and the particle model

A Qualifying Paper

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Brian E. Gravel

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Advisor: Prof. Bárbara Brizuela
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Abstract

In this paper, I report research on students’ production of multiple external representations of air and the particle nature of matter. The process of externalizing one’s understanding helps to strengthen and develop ways of seeing the world. Students engaged in a process of representing their ideas across multiple forms cultivate a stronger, richer understanding of the content. In addition, such a multi-modal exploration provides the researcher with a diverse array of ways through which to view students’ understandings of science concepts. In the present study, four 8th grade students attending an urban public school expressed their understanding of air as a substance through four systems of representation: oral language, drawing, stop-motion animation, and the construction of physical artifacts. The findings elude to a relationship between the conceptual aspects of air externalized and the forms of representation under investigation. Specific contexts evoke specific aspects about air. While these findings can not be generalized, the research provides researchers with multiple routes of access to children’s ideas about science, including their emergence and materialization. For students, the results emphasize the importance of providing them multiple opportunities for inventing ways of expressing their ideas about science as a means for developing a deeper understanding of scientific concepts.
1.0 Introduction

The study reported in this paper investigated the use of multiple systems of external representation in explorations of fundamental science concepts, in this case air and the particle model of matter. Previous studies in mathematics and science education research have been carried out in the area of multiple representations (Brizuela, 2004; Brizuela & Earnest, 2008; Goldin, 1998; Lehrer & Schauble, 2000a, 2000b; Nemirovsky, 1994; Pozo & Gómez Crespo, 2005; Johnson, 1995; Zhang, 1997; Zhang & Norman, 1994). However, the present study strongly emphasizes the role of production of external representations – spontaneous, student-generated and sometimes idiosyncratic representations – across multiple systems, a topic receiving less attention in the science education literature. Previous research has documented students generating insightful representations about science concepts through conventional systems of representation (oral language, written language, mathematical notation, etc.; discussed further in Section 2.3) as well as through less common, hybrid systems such as creating animations or constructing physical artifacts (see Martí & Pozo, 2000). For example, through the process of generating stop-motion animations, middle and high-school students have represented rich understandings about topics such as parabolic motion, which is traditionally a difficult concept for students to learn (Church, Gravel, & Rogers, 2008). While conventional systems of representation such as mathematical notation and written language are used broadly in school science, hybrid representations, such as stop-motion animations, are rarely used in schools; this deficiency could be limiting students’ abilities to represent complex and intricate understandings. Bamberger (1991) eludes to the uses of non-traditional forms of representation when she notes:
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)

Bamberger’s message extends beyond students’ gaining knowledge of symbolic systems: students engaged in multiple, varied ways of representing their knowledge possess greater opportunities to develop their understanding and their ability to express that understanding in new ways. Additionally, the multiple representations provide the researcher with multiple ways of viewing the student’s understandings. While externalizing ideas through multiple systems likely improves one’s understanding of symbolic representations, it can benefit an individual’s conceptual understanding as well. Therefore, the present study aimed to give students opportunities to explore a common, yet quite complex, concept—air and a particle model of matter\(^1\)—using multiple means of representation. It was my hypothesis that students would display different aspects of understanding through different systems, while concurrently developing their understandings of air and the particle model of matter.

The particular content topic for this study, air as a substance, was chosen for a multitude of reasons. Nearly eight decades ago Piaget (1930/2001) reported studies involving young children’s conceptions of air and wind. He found that young children often associate air with

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\(^1\) I choose the term “particle” in the present work to be synonymous with “particulate”, as used by Nussbaum (1985).
examples of objects being moved by air currents, such as wind moving the leaves on trees. From this point of view, there needs to be some observable effect in order for air to be recognized. Students as young as five years old are familiar with the term “air”, thus, one can argue that students have encountered the idea from a very young age. While air is used in everyday, nonscientific conversations with great frequency and can even cause observable effects (e.g., moving tree leaves), it remains "unseen," which can lead students to develop alternative explanations for effects caused by air based on their prior knowledge. These ideas are often called "naïve" and describe the spontaneous knowledge students posses (McCloskey, 1980, 1983; Vosniadou, 2002). Students’ naïve ideas about air (in both static and dynamic states) coupled with the unseen nature of air make it a rich topic for researching multiple modes of representation in students’ making sense of science. Unseen agents (e.g., air, gravity, sound) are conceptually rich topics because while one can observe the effects of such agents, one must make explicit the mechanisms of change in some other way. For example, in order to explain how a shift in air pressure in a room can cause a door to close, a student must make explicit the mechanism he or she believes was responsible for the action. In the process of asking the student to generate this explanation, the researcher can gain a unique perspective into how the student makes sense of the situation. With unseen agents, one gains a unique window into not only how students make sense of science concepts, but how they choose to externally represent these concepts. Thus, the unseen nature of air makes it a compelling topic for investigating relationships between conceptual ideas and external representations. And given that air is a mixture of gases, students’ ideas about air are intimately related to their understandings of the particle model for matter. Thus, while air is the focus of the study, students’ ideas about particles are encompassed by the topic. The study presented here is grounded in a theoretical framework
of the fundamental role that multiple external representations play in the development of scientific understanding.

1.2 Models and multiple representations in scientific practice

The language of science is multiple representations; scientists use drawings, graphical notation, mathematical symbols, written language, oral language, and models to communicate their findings and to fuel future discovery (Chapman, 2000; Garcia-Mila, Andersen, & Rojo, 2009; Ochs, Jacoby, & Gonzales, 1994). The domain of science concerns itself with generating models of phenomena and the ways in which these models are shared and discussed is through multiple forms of representations. Constant testing and refinement of said models involves re-representing the ideas across a variety of expressive media. Thus, the ways in which scientists communicate ideas is intimately dependent on multiple representations. For example, we have overwhelming empirical data suggesting that two massive bodies are attracted to each other by a gravitational force. Before the apple fell on Sir Isaac Newton’s head, gravitational force existed, but it was not until he developed a mathematical model for this concept that it could become as important in the scientific discourse as it is today. Models and the ways of representing these models are fundamental elements of science, however, defining the term model relative to students’ ideas about science is an arduous task. The term model has taken on numerous meanings, depending on the domain from which the term is considered (Clement, 1983, 2008; Lehrer & Schauble, 2000a; Justi & Gilbert, 2000; Stewart & Golubitsky, 1992; Vosniadou, Skopeliti, & Ikospentaki, 2005), highlighting the need to articulate the ways in which scientific models are similar and dissimilar to the models students use when making sense of the natural world.
I propose that students hold ideas, which are similar in nature to scientific models, however, students’ models likely resemble science models of antiquity. Aristotle believed that heavy things fall faster; Galileo revised that model (by rather famously dropping balls from the Tower of Pisa); and Newton derived a mathematical relationship that elaborated on Galileo’s model (Gribbin, 2002). The history of gravity highlights how models are tools for thinking about how the world works. Stewart and Golubitsky (1992) describe the scientific method as deeply dependent on models (i.e., mathematical descriptions) that, “capture essential fragments of how [scientists] think the world behaves” (p. 2). They argue that scientists use these models to develop theories that can be tested with hypothesis and experimentation. The models are revised in an iterative fashion until the theory and experiment agree (which is a rarity). Thus, models are dynamic, evolving tools that scientists use to make sense of the natural world. It is reasonable to suggest that students, too, develop models (although hardly scientific, in the stricter sense) to help them understand how the world works. Lehrer and Schauble (2000) argue that students can be considered as natural modelers, who are able to see how certain ways of conceptualizing phenomena are useful in multiple contexts. This is not to suggest that students hold coherent, generalized models in the scientific sense, but rather that students develop certain ways of making sense of phenomena that can be treated much like scientific models.

The process of developing and refining models is inextricably linked to the forms of representation through which the models are expressed. In other words, inherent in the revision of models is the development of new ways to represent and communicate the ideas of science. The importance of modeling in science is widely recognized, and the way in which models are developed is through the use of external representations, which are the focus of this paper. When scientists are debating the intricacies of phenomena, they are arguing with graphs, mathematical
equations, drawings, diagrams, written language, spoken language, and even gesture. In other words, scientists “talk” through a multitude of representations. For students, the external representations that they produce are often idiosyncratic and non-normative, however, they are important elements in the process of constructing scientific understanding. Therefore, models and representations are fundamentally different, but both intrinsically important to understanding how the world works. In summary, an examination of the role representation plays in how students use models (either implicit or explicitly) to construct knowledge is crucial to the field of science education, and the present work is an attempt at this examination.

1.3 Process vs. Concept

The term representation as used herein namely refers to externalizations (i.e., events or objects perceivable by others). External representations have an important duality that make them a valuable lens through which to analyze how students develop understanding. The distinction is based 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 (or tool, in Douady’s (1997) terms) and object. From one perspective, the operations or actions required to represent a scientific or mathematical concept can be considered as a process. For example, in mathematics, a function can be seen as a “method for getting from one system to another” (Skemp, 1971, p. 246). This definition of function reflects an operational conception (Sfard, 1991); functions are considered as a process through which to achieve some transformation. For students developing an understanding of functions, the approach to the concept is from a process perspective, where the function is a tool (Douady, 1997) for doing something. Similarly, consider the development
of written language. A student’s understanding of written language is a constructive process, where the use of idiosyncratic inscriptions and conventional letters are tools for conveying ideas (Ferreiro, 1994). It is not until the student has developed sufficient understanding of the written language system that they can begin to consider words as objects that represent ideas that can be reflected upon. Sfard (1991) argues that (in mathematics) “the majority of ideas originated in processes rather than objects” (p. 11). For students, the development of knowledge and of a capacity for representing understanding through various forms begins as a process as well.

Students grow up in a world that is filled with conventional systems and idiosyncratic forms of representation. They experience oral language, written language, graphs, gestures, pictures, moving-pictures, and a myriad forms of representations. Once the semiotic function begins to develop, children begin to experiment with and refine how they represent their understandings. Living immersed in a world full of symbols and signs, it is to be expected that this process of representing will be influenced by exposure to and interactions with various forms of representation—representations laying in a world “external” to the student and capturing a historical trajectory of some nature on the part of humankind. Furthermore, the process of representing as essentially referential-communicative in nature (Tolchinsky-Landsmann & Karmiloff-Smith, 1992) yields a physical artifact or action perceivable by others (e.g., gestures, writing on paper).

These artifacts become conceptual objects in their own right (Olson, 1994), whereby the object, while being a representation, is perceived as the referential concept. This structural conception (Sfard, 1991) of representations allows the individual to reflect upon the concept as embodied in the external representation. Therefore, external representations can be both a process and conceptual objects. However, establishing a strict dichotomy might not be very

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2 At around 18 months of age, according to Piaget and Inhelder (1966/1969).
helpful, because students involved in explorations of new ideas likely transition between process and object aspects of representation as they construct an understanding. Representations as conceptual objects are pivotal in the development of thought, as placing an idea in the external world allows for reflection and evaluation of one’s understanding (Kaput, 1991). By making knowledge explicit through a process of externalizing ideas, students strengthen and develop their conceptual understanding (Lehrer & Schauble, 2002; Schliemann, Carraher, & Brizuela, 2007; Tytler & Prain, 2007). In addition, the artifact (i.e., conceptual object) provides the researcher with a perspective regarding what the student knows (Kaput, 1998). Eventually, the external representation becomes a fundamental element of any understanding. Representation is a process whereby students explicate their knowledge, resulting in a conceptual object that is part and parcel of thought. In other words, 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. In the context of students’ understanding of science, the process and object characteristics of representation should be concurrently considered, as both help the student reason and think about scientific phenomena.

1.4 Representations as thought amplifiers

According to Piaget’s theory, young children are egocentric and unaware of the world outside that which they can directly perceive. Through a process of decentering (also known as the Copernican Revolution; Piaget & Inhelder, 1966/1969), the child recognizes his or her existence as one object in a universe of many independent objects. Having come to this juncture, the child knows of the existence of objects beyond him or herself, and subsequently develops a need for a

Moreover, representations are dynamic constructions, which means that once they are established at a personal or social level as objects, they may continue to evolve so as to capture new shades of meaning.
mechanism to re-present that which is perceptually absent. Piaget calls this mechanism the *semiotic function*, and it provides the child with the ability and power of representation. Decentering allows a child to recognize the existence of a causality that is “both localized in space and objectified in things” (Piaget & Inhelder, 1966/1969, p. 13), which forms the foundation from which she will develop reflective and, eventually, abstract thought. From this perspective, representations are seen as *thought amplifiers*, as they allow more abstract and complex ideas to be contemplated by children and adults alike.

The perspective that representations are essential to formal thought is primarily a Piagetian construct (Piaget & Inhelder, 1966/1969), however, the idea has much broader implications. In the world of mathematics and science, the use of multiple forms of representation (both internal and external) is heavily relied upon for the general activities of professionals in the field. Producing representations effects young children, but externalizing knowledge also has an effect on scientists who are fluent with several systems of representation (e.g., mathematical notation, graphical notation, written notation). Knowledge objectified in representations is accessible for reflection and abstraction, making the external artifact a means for amplifying thought. When combined with other representations, scientists and children alike are afforded an opportunity to reflect on a number of concepts simultaneously. Thus, the representation serves as a vehicle for heightening the level of conceptual complexity. 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 conceptualizing the concepts of the domain. In this sense, the representation amplified thought to
the degree of influencing fundamental concepts in physics. However, Feynman’s diagrams were not initially adopted, and it was a process of introducing representations and refining them to optimize their purpose that made them powerful; a process that is related (in some sense) to students’ attempts to represent new ideas in mathematics and science.

1.5 Progressive symbolization

When a student writes or draws something, that externalization, we assume, is linked to an understanding in the mind. 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 relation between whatever idiosyncratic representation they produce and their own understanding as well (Goldin & Kaput, 1996; Lehrer & Schauble, 2002). There is a process of production and realignment that deeply impacts how students represent their ideas, and the work of diSessa, Hammer, Sherin, and Kopalkowski (1991) on students’ inventing graphing highlights this process.

In a relatively short intervention (five class sessions) with sixth-grade students in Oakland, California, diSessa et al. (1991) illustrated that students have a natural ability to invent and critique representations. Students were presented with the following scenario:
A motorist is speeding across the desert, and he’s very thirsty. When he sees a cactus, he stops short to get a drink from it. Then he gets back in his car and drives slowly away. (diSessa et al., 1991, p. 125)

Each student was charged with putting something on paper that described the motion of the motorist. The students’ first attempts at representing the scenario yielded idiosyncratic notations based on lines, dashes, dots, and other relatively generic shapes. Discussions about each notation lead to realizations by the students that more than one dimension needs to be included in a representation of the motorist’s trip. For example, some of the initial drawings only represented changes in speed without consideration of changes in time or distance. Through revisions of their original notations, the students developed more complex notations showing distance and time. In each successive revision, the conversations between the students and the teacher served as a way for each individual to find some meaning in the newly produced form. Each student needed to match the specific version of the representation with his or her understanding of the motorist’s path through the desert. Eventually, the students came to an agreement on a final representation for speed, distance, and time that was a position versus time graph – a conventional method for representing motion. diSessa et al.’s (1991) work highlights two critical elements of students inventing representations. The first is that through invention and critique of representations, students can develop and appropriate (when mediated by an expert, in this case the teacher and researchers) conventional means of representing information (see also Enyedy, 2005). The second important element to this episode is that any externalization of knowledge requires an accompanying connection between the artifact and each student.

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4 The term notation is used in reference to markings on paper that students generated in the diSessa et al. (1991) study. Notation (which is a form of external representation) is the term used by diSessa et al. and in the interest of consistency we have chosen to use the term in this section. In the remainder of the paper, the term representation is used as to encompass notations, inscriptions, and other commonly used terms.
individual’s understanding. Even when the individual produces the representation (as opposed to viewing one that someone else produced), he or she critiques the artifact, and inherent in that critique is the creation of an association between the external artifact and the ideas the individual holds about the particular situation.

Many researchers have shown that students have a powerful ability to critique representations (Danish & Enyedy, 2006; diSessa et al., 1991; diSessa & Sherin, 2000), and such evaluations of the artifact are central to the reconstruction of the link between the object and the signified. 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 knowledge to be a performance, whereby the student is demonstrating some aspect of knowledge. This practice of active, real-time sense-making accurately describes how the student produces and reflects upon a representation, as to rebuild the link between idea and object. 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. This “second generation” representation undergoes the same re-linking process described in a “progressive symbolization” (Enyedy, 2005; Lehrer & Schauble, 2002) process. 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). Alternatively, Karmiloff-Smith (1990) proposed representational redescription as a similar construct, where students undergo developmental changes whereby
they represent elements of the same knowledge in progressively more abstract ways over time\(^5\). Students regularly engage in such progressive or re-representational activities, particularly in mathematics and science learning, which leads to increasingly complex understandings of the particular domain of study (Lehrer, Strom, & Confrey, 2002). An example is the lengthy process of students coming to appropriate the conventional forms for writing numbers. Although they may begin to use the forms of written number from a very early age (around 3 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 redescriptions of the written forms to align with (and perhaps advance) students’ understandings of number and the logic of the system. Underlying this process of change is the a pattern of students iteratively or cyclically producing and refining representations of knowledge, and such refinement is heavily influenced by the ability of the child to re-construct a link between object and idea. For example, students inventing methods for mapping height showed a progression from overhead representations to eventually creating and adopting topographical lines to represent changes in height (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 aligned with the understandings of the students\(^6\). The act of representing and re-representing to refine knowledge (Waldrip, Prain, & Tytler, 2008), and to define the symbols themselves, is analogous to what scientists and mathematicians do in their respective domains.

\(^5\) Karmiloff-Smith’s (1990) *representational redescription* 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.

\(^6\) I take care to note that this alignment is never static, as the representation and conceptual understanding are dynamic and undergo frequent revision and development.
In a domain such as Theoretical Physics, efforts to generate new models that simplify the representations of concepts are a driving force for the field. In doing so, scientists utilize conventional systems of representation as well as introduce new elements to better describe the concept, such as with the Feynman Diagram. Students engaging in progressive symbolization go through a similar process. As they objectify knowledge, they will slowly incorporate and appropriate elements from conventional systems of representation. Eventually, students come to learn the conventions and how they are used. The iterative process described is an example of how externalizing knowledge can serve as a thinking tool: by becoming object, it allows us to reflect on our representations, verify our thoughts, and contrast between different understandings and representations (diSessa et al., 1991; Kaput, 1991). It also highlights the importance of conventional systems of representation, the origins and development of which are deeply influenced by cultural factors.

1.6 Cultural motivations of representation

The development of the ability to represent knowledge is shaped by a multitude of factors, not least of which is culture. Vygotsky (1978) suggested that students develop understanding through processes that are mediated by both adults and artifacts of a particular culture. In other words, “the special quality of the human environment is that it is infused with the achievements of prior generations in reified form” (Cole & Wertsch, 1996, p. 2), and these achievements are what mediate the development of understanding in students. Individuals belonging to a particular cultural group will develop means of expression and artifacts that embody shared meaning. Vygotsky suggested that these tools include “various systems for counting; mnemonic techniques; algebraic symbol systems, works of art; writing; schemes,
diagrams, maps, and mechanical drawings; all sorts of conventional signs, and so on” (Vygotsky, 1981, p. 137). Such products of culture become conventional means of representing and acting through a process of finding shared meaning. In other words, a desire to communicate will drive a culture to invent ways of talking, writing, or even gesturing that all members can use and understand. One could make the case that all representations embody, on some level, aspects of their native culture because they serve as vehicles for interactions among individuals (Cole, 1996; Nelson, 2009; Vygotsky, 1978). The conventional ways of representing ideas deeply impact how students come to express their knowledge, and language is considered to be one of the prime examples of a cultural invention that mediates representations of understanding. This is why Vygotsky put language at the forefront of his theory of development, for language is what opens the doors for many students to begin experimenting with externalizations (Vygotsky, 1962).

When students begin developing the ability to represent ideas, through language or any other form (i.e., gesturing or drawing), they are doing so within a cultural context laden with conventional systems. And while learners may not master the conventions, these cultural standards influence how students spontaneously represent knowledge at younger ages and how they eventually come to master and appropriate (granted, each individual with his or her own particular signature and flavor) a conventional system such as written or oral language, or the written number system. The conventional systems serve as a gateway for learners to begin to understand the more complex and abstract conceptions that are prevalent in their particular culture. While culture shapes representations, it also shapes the use of these tools and the nature of knowledge. Conventional systems are developed by cultures as they negotiate a shared meaning about a particular concept (Confrey, 1991). Convergence of meaning amongst
members of a culture (e.g., engineers or physicists) results in such negotiations which center on the external representations of the concepts in question (Confrey, 1991; Roth & McGinn, 1998). Integrated within these negotiations are decisions and agreement about what symbols are to be used and how they are to be used to represent which conventional ideas. Thus, those ideas that are accepted by a particular culture may be interwoven with their collection of conventionalities. In fact, representation systems such as written language and the mathematical notation systems are products of human attempts to describe and share meaning over millennia. Thus, the role of social interaction and negotiation plays a crucial role in how conventional representations come to be, as well as in how students come to know and use these systems in order to express their ideas.

1.7 Representations as the centerpieces of negotiations of meaning

It can be argued that a concept as we know it (e.g., gravity) does not exist without its accompanying representations. The scientific concepts humans have agreed upon to be “true”, or to “exist”, are dependent 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 discovers a new phenomena (which I acknowledge can impact the world before a representation of that concept has been developed), he or she constructs a means for communicating this new idea to the scientific community. For the domain expert (i.e., scientist), such a representation will likely include elements from conventional systems such as graphs or mathematical notation. Once the idea is objectified in the artifact, conversations regarding the validity, robustness, and accuracy of the proposed concept eventually decide its fate. For some, the representation chosen by the discoverer may not be suitable and, thus, may be modified to
satisfy concerns. Others may accept the representation but challenge the methodology through which the evidence for such a phenomenon was generated. For example, when Einstein proposed his special theory of relativity, which revealed the equivalence of mass and energy with the famed \( E=mc^2 \) algebraic representation, it was of limited impact on the field of physics (Gribbin, 2002). It is inaccurate to say that his contemporaries did not understand his theory, but the ideas did not make a significant impact until translated into four-dimensional geometric terms (Gribbin, 2002). At the time, algebraic notation and geometric notation were both conventional in science; however, it took some negotiation and discussion before the field came to unanimously accept the theory as robust and powerful. At the center of the discussions around newly introduced concepts is an externalization of some knowledge, and eventually the community will come to either reject the idea or find shared-meaning in the representation which would elevate the idea to a level of consensual knowledge (Kaput, 1991). We need to call attention to the inherent pattern existing within this negotiation of meaning (Confrey, 1991). Progressive symbolization, as described above from the standpoint of the individual child, can now be expanded to include the role of social interactions in learning to represent (Danish & Enyedy, 2006). 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 concept. Therefore, the inherent pattern found in instances of meaning arriving from negotiation is present within the individual and within cultural contexts.

### 2.0 Defining representation

Representation is a somewhat ubiquitous term in many fields of social science research, with a variety of definitions and usages. Kaput (1985) suggests that representation is an
“undefined primitive 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 difficult to define. The literature suggests a diversity of definitions for representation: Enyedy (2005) offers that representation is “the act of highlighting aspects of our experience and communicating them to others and ourselves” (p. 427); Goldin and Shteingold (2001) suggest 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) affirm the belief 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). Thus I will first consider representation in a broader sense, as constituting some measure of “stand for” or “refer to” relationship.

2.1 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). At the most basic level, representation has been treated as a “stand for” (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.\(^7\)

\(^7\) For the purposes of the present argument, we 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 a certain purpose – for example, a child using a banana as a telephone. 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
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, continually varies the meaning of representations depending on context and situation (von Glasersfeld, 1987). Thus, while there are conventional systems, there are not always conventional meanings. Some have a tendency to believe that words and images have an embodied meaning that exists as such, without interpretation. While this may be true on some level and for individuals with command over a conventional system, there are always variations in meaning to be found among these individuals, and students engaged in the process of learning to create representational relationships are in any case unaware of these pre-determined correspondences between signifier and signified. As von Glasersfeld (1987) states:

Because perceiving, from a constructivist point of view, is always an active making, rather than a passive receiving, the similarity of a picture and what it depicts does not reside in the two objects but in the activities of the experiencer who perceives them. Ordinary language, however, refers to objects as though they existed as such, independent of experience. Consequently, it always leads us, the language users, to attribute differences in our perceptual operating to the externalized objects as though there were properties belonging to them in an “objective” sense. Provided we remain aware of this epistemological sleight of hand, we may safely say: An iconic representation...is an

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. The two terms are, thus, considered interchangeable herein, but the existence of potential differences between the representational relationships each term implies is duly noted.
artifact and a deliberate reconstruction of another experiential item; the reconstruction selects certain properties considered relevant under the circumstances. (p. 217)

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); this would constitute the process of representing, as discussed earlier. de Saussure’s arbor versus tree example (see de Saussure, 1959) also highlights a controversial dualism in representation research, which is closely linked with the discussion of the process view of representation. This dualism is the distinction between internal and external representations.

2.2 Internal vs. External representations

Literature reporting traditional approaches to cognitive research has regarded representations as existing 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. Others have supported Donald by focusing on external representations (i.e., those displayed on bidimensional spaces, such as writing, numerical notation, and drawing, and those that are not, such as gesture or spoken language; Even, 1998; Martí & Pozo, 2000). According to Donald (1991), external representations of memory are mechanisms of cultural evolution and of the development of the modern human
mind. Goldin (1998) defines *external representations* as "the shared, somewhat standardized representational systems developed through human social processes" (p. 146) supporting the belief that cultural evolution plays a critical role in the development of these systems. However, before the issue of systems of representation can be fully explored, the distinction between *internal* and *external* representations must be addressed. Goldin and Kaput (1996) state that, "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 as a classification scheme 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, raise the question: by focusing on external representations, “are we establishing an absolute frontier between outer and inner worlds?” (p. 7). They warn 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 have warned is a dangerous trend in representations research.
(Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009). As previously mentioned, the act of externalizing understanding involves a remapping of that conceptual object to the understanding one has. Such a process of remapping is exactly what Nemirovsky (2009) speaks toward; students do not copy what they perceive onto their mind; rather, they reconstruct connections between perception and understanding. Thus, when the focus is placed on internal versus external representations, the constant interplay between understanding and externalizations is essentially ignored. As some researchers have suggested (Nemirovsky, 2009; Pérez Echeverría & Scheuer, 2009), the focus needs to be placed on the inscriptions, notations, and symbolic expressions\(^8\) that students produce in particular learning environments, always keeping in mind that none of these constitute direct windows into their internal representations\(^9\).

The present work is primarily concerned with externally produced expressions with a physical presence 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). It is important to remember that even though in this paper I may focus on students’ productions of external representations, I certainly acknowledge the lurking presence of “the phantom of duality.” In working with students in educational settings, the only primary source of their understanding that we, as researchers, have access to are the notations, inscriptions, drawings, gestures, and speech that they produce. Each of these modes of

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\(^8\) 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.

\(^9\) A possible alternative could be to refer to external representations as “externalized representations” (Scheuer, personal communication, March 4, 2009), which acknowledges the role of the ideas and thoughts the child holds. 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, we retain the term external representation herein to keep consistency with the terminology used in the literature.
expression can be organized into a system of representation (Gardner & Wolf, 1983; Goldin & Shteingold, 2001; Nemirovsky, 1994), which are useful constructs for considering how students learn and appropriate representations.

2.3 Systems of representation

Some 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 conventionally used as 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. 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). Goldin (1998) cites “systems of spoken symbols, written symbol, static figural models or pictures, manipulative models and real world situations” (p. 143) as examples of systems of representation. Nemirovsky (1994) differentiates "symbol use" from "symbol systems" by maintaining that systems involve rules. Recall the role of cultural evolution in the development of representations. As conventional systems of representations used as referential-communicative tools are created, rules are simultaneously developed (either implicitly or explicitly) as means for preserving common meaning found in the relationships between signifier and signified. Thus, the rules that govern the use of elements evolve so that the signs of a given system may be consistently mapped to shared intended meanings.

As students externalize their understandings in particular systems of representation, 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 rules. For example, when two people speak colloquially, there may not be an agreed upon set of rules for that system of spoken language, but they are still able to represent meaning. Lehrer and Schauble (2000a) use 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). Thus, a need arises for a classification scheme for systems of representation with similar rule systems, as this will help in classifying how students learn to represent knowledge. Pérez Echeverría and Scheuer (2009) offer an interesting classification scheme for external representations with four major kinds of external representations: (1) bodily and gestural representations, (2) oral language, (3) notations based on relatively relaxed combination rules (i.e., drawing, maps, and graphs), and (4) strict notational systems\(^{10}\) (Pérez Echeverría & Scheuer, 2009). According to this taxonomy, there can be systems of representation with formal rules and different systems built on relaxed, idiosyncratic rules. The authors purport a second axis of dimensionality to the classification scheme, which is a temporal – spatial scale. Consider gesture and oral language as two systems of representation, whereby gesture has largely idiosyncratic rules and oral language is governed by much more formalized and conventional rules (i.e., grammar). As Pérez Echeverría and Scheuer (2009) suggest, the physical distance between the individual producing the representation and the individual receiving the representation widens as one moves from gesture to oral language. In order to interpret a gesture, physical proximity and visual contact between the producer and receiver must occur. However, oral language communication can occur without visual contact with one another, and given the introduction of phone or internet

\(^{10}\) Pérez Echeverría & Scheuer (2009) acknowledge that there are additional forms of external representation left aside, including deaf sign language, reading and writing Braille, video and film, written records of choreographies, and combined use of several external representations in computerized environments.
technologies into communication, oral conversations can take place over great distances\textsuperscript{11}. While physical proximity is an important factor between oral and gestural representations, those externalizations which produce a physical artifact (e.g., notations, inscriptions, etc.) can exist over a longer temporal dimension as well. Representations of ideas that yield a physical artifact are perceivable over long periods of time, across contexts, and across cultures. The lasting nature of such representations may make them more useful in reflective thought or in aiding memory (Pérez Echeverría & Scheuer, 2009). Thus, systems of external representation appear to have both temporal and spatial qualities, which offer different benefits and limitations in different contexts. Analyzing systems of representation using such a construct, where the structure of a rule system comprises one dimension of the system and the temporal–spatial constraints comprise the other leaves the impression that these systems are separable. While they may be separable in terms of research, “they continually coalesce in everyday activities” (Pérez Echeverría & Scheuer, 2009, p. 6). 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) shows 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, their conceptual dilemmas arise as they attempt to represent ideas with which they are uncomfortable. Brizuela (1997, 2004) reports on the introduction by a young child of “capital numbers,” a term used in reference to the first digit in a two-digit number. The young child, not knowing that a

\textsuperscript{11} Technology has complicated the ability to characterize systems of representations in this way as recording devices have become relatively ubiquitous. Gesture can be conveyed over distances using video conferencing equipment or even video recordings. However, the classification scheme remains useful in attempting to make sense of how students come to operate within and through these numerous systems of representation.
digit in the tens place of a numeral was called, referred to it as a “capital number.” As with the first letter of a sentence or a proper noun, which is capitalized in the English language, the student “borrowed” this term in attempts to conceptualize two-digit numbers (Brizuela, 1997, 2004). While students may tend to use a conventional oral representation of the number (i.e., the child will say “thirty six”, not “three six”), their understanding of the rules of the written system may not be fully developed. As a result, the child invents a solution to the problem: one may be using “capital numbers” to refer to the tens digit in a two-digit number. Brizuela (1997, 2004) also alluded to a larger issue, which is that “learning and constructing knowledge involve inventions – novel productions we create, using our present cognitive structures, while trying to make sense of a situation or phenomena” (p. 35). The child’s efforts to borrow from one system to make sense of another ultimately leads to a constructed understanding of the particular rules of a given system. 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 where they can find meaning. This is an important point to keep in mind while researching how students produce external representations. While some of the artifacts may appear meaningless from the perspective of a developed system of representation, in reality the artifact has meaning to the child, and this meaning should be explored. Therefore, researchers must value how students represent spontaneously, how they learn to represent, and how they come to learn the common rules associated with specific systems of representation, be they formal or informal.

Yerushalmy (1997) also calls this “manipulating the conventions” (p. 452), where students find new meaning in conventional representations to suit the needs of a particular problem.
3.0 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). Others have made a similar argument, where attempts to express knowledge across systems of representation are shown to be beneficial for conceptual understanding (Brizuela & Earnest, 2008; Lehrer & Schauble, 2002). One specific reason for the benefit of 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 used in this section in two different manners: expressively and interpretively (Toth, 2000), or perhaps more classically production and comprehension (Eskritt & Lee, 2007; Lee & Karmiloff-Smith, 1996a). An expressive representation or production is created by an individual in attempts to convey information to oneself or to a broader audience. These externalizations can be idiosyncratic, conventional, or a combination of both. Representations in an interpretive sense are those which the individual encounters in some environment for which he or she must display some measure of interpretation or 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 productions and comprehensions will be included in this review.

The research in science and mathematics education has provided evidence that students can develop richer conceptual understanding 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 in which aspects of the problem are made apparent; highlighting a variety of conceptual aspects through multiple representations fosters deeper insight for students (Confrey, 1991). Highlighting conceptual elements of the same problem can support students’ finding 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) suggests, for many individuals (students and teachers), unpacking the problem involves the exploration of many forms of that problem; that is, “different kinds of conceptualizations…can be explored by navigating across different representations of the same problem” (Brizuela & Earnest, 2008, 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 that “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 motion through two different representations with middle school students. 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 charged with comprehending representations that were presented to them in computer software environments (Parnafes & diSessa, 2004). Interpreting and making-sense of representations across multiple systems has been shown to have an impact on students’ understanding of math and science ideas. However, gains in understanding have also been shown when students generate the representations across multiple systems. While some have shown the power of comprehending representations, instances of students producing representations are also powerful contexts for impacting understanding (Toth, 2000)\(^\text{13}\).

Brizuela and Earnest (2008) report 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, Mayer, Moseley, Brar, Duran, Smith, et al. (1997) showed similar results in algebra, whereby when students were introduced to new representations for problems,\(^\text{13}\)

\(^{13}\) 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 new conceptual areas.
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’s (2007) study in the domain of science confirmed these previous findings, showing that as students constructed 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). The common theme running through these studies is that the exploration of concepts by students generating multiple representations results in increased conceptual understanding. 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 the concept in each of the systems yields a benefit (Friedlander & Tabach, 2001). Students as well as teachers can pose appropriate questions, with the appropriate guidance and structuring (Lehrer & Romberg, 1996). No matter who generates the problems, their appropriateness in addressing the concepts at hand must be considered. Just as the representational effect (Zhang, 1994) suggests, not all representations are best suited for all problems and thus, before students have gained representational competency, care should be taken in selecting the kinds of problems used to help teach students how to externalize knowledge.

The study I report in this paper concerns how students externalize their understanding of science concepts across multiple systems of representation, and how the process of externalizing impacts their particular understandings. The specific concepts of interest for this study are air and the basic particle theory of matter.
4.0 Students’ conceptions of air and the particulate theory of matter

Modern science views air as a collection of gases described by the particle model of matter, stating that (1) matter is made of particles called atoms, which are too small to see with the naked eye; (2) particles are in constant motion; (3) there is empty space (a vacuum) between all particles; (4) particles are held together by strong attraction and repulsion forces; and (5) the interactions between particles determine the observable properties of matter (Johnson, 1998a). However, the Kinetic-Molecular Theory of Gases (Halliday, Resnick, & Walker, 2005) more specifically addresses the behavior of substances in the gaseous state, such as air. The 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. Students’ conceptions of air, air pressure, and the particulate nature of matter are well documented in the literature (Brook, Briggs, & Driver, 1984; deBerg, 1995; Driver et al., 1994; Johnson, 1998a, 1998b, 1998c; Nakhleh, Samarapungavan, & Saglam, 2005; Novick & Nussbaum, 1978, 1981; Nussbaum, 1985; Papageorgiou & Johnson, 2005; Piaget, 1930/2001; Pozo & Gómez Crespo, 2005; Séré, 1982; 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 from a very young age that must be considered independently from pure gases. Thus, both the literature on air and the literature on the particle model inform the present work, and are reviewed accordingly.
4.1 Students’ conceptions of air

Piaget (1930/2001) published some of the first work on young students’ conceptions of air, pressure, and wind. Students of young ages, Piaget found, hold strong beliefs about the relationships between air and movement. For example, clasping two hands together and generating pressure between the palms will yield a small current of air, which students of different ages conceptualize in different ways. Younger students do not believe that there is air inside a room and that it only exists outside (i.e., in nature). Older students, however, eventually come to realize that there is air inside the room, and that the hands simply create a small stream of air movement. Similarly, younger students tend to believe that trees generate wind, while older students come to recognize the role of air currents in moving the leaves on trees. Piaget’s (1930/2001) work paved the way for others to examine the relationship between movements and air. Seré (1982) found that young students associate a movement with the presence of air (such as with wind). However, this study focused on students of middle-school age (approximately 12 – 14 years of age), and most studies suggest that students this age are already aware of air in static conditions (Séré, 1982; Driver et al., 1994; Tytler, 1998). Focusing specifically on air as a substance (as opposed to air pressure), students of this age can conceive of air (Séré, 1982), some recognize the existence of an atmosphere (Driver et al., 1994), and many students recognize 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 admit that air “pushes against things,” and some students specify the direction of force, claiming that air can push things forward (Driver et al., 1994). However, 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 with the composition of the substance. The literature on air
reports conceptions that appear plausible if we subscribe to the belief that understanding is constructed from experience. Students are comfortable with the idea of air and the effects it causes, because these are familiar situations. However, the science of air as a mixture of gases explained by the particle nature of matter is considerably more complicated and precise; students have the task of reconciling the scientific understanding of air and its effects with their more everyday experiences.

4.2 Students’ conceptions of the particle nature of matter

Fensham (1994) argues that the widespread failure of students to accurately conceptualize the particulate model of matter suggests that the teaching of these concepts should be delayed. 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. The literature suggests that students hold alternative ideas than what modern science purports (Brook, Briggs, & Driver, 1984; Novick & Nussbaum, 1978, 1981), however, elements of students’ thinking can be useful in the construction of normative ideas (see diSessa et al., 1991). Specifically, Brook, Briggs, and Driver (1984) found that greater 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.

Students in upper elementary and middle schools focus on bulk, macroscopic properties of air (Novick & Nussbaum, 1978; Pozo & Gómez Crespo, 2005) before being introduced to a particle model. Once the particle model has been introduced, students tend to prefer this
representation (Novick & Nussbaum, 1978), but continue to hold alternative ideas about how particles are spaced and how they interact (Brook, Briggs, & Driver, 1984; Johnston, 1990; Novick & Nussbaum, 1978, 1981; Pozo & Gómez Crespo, 2005). However, despite alternative conceptions, students develop a belief in a uniform particle distribution as students progress through grade levels (Novick & Nussbaum, 1981). The concept of “empty space” between particles remains challenging for students through high school and potentially into college (Driver et al., 1994; Johnston, 1990; Novick & Nussbaum, 1981). To summarize, the literature on air and the particulate nature of matter supports a belief that students hold ideas about particles that may not be normative, but are useful in the construction of more scientifically accepted ideas. Johnson (1998a, 1998b, 1998c; Papageorgiou & Johnson, 2005) presents a way of considering students’ developmental progression with respect to a particle model that honors their attempts to make sense of the unseen, relatively abstract concept of air as particles. This work informs both the design of the study reported in this paper as well as the analysis of the data presented herein.

Johnson (1998a) conducted a thorough review of the literature on students’ ideas about the particulate nature of matter prior to conducting a longitudinal study on this topic. He presents (Johnson, 1998a) a developmental progression for students’ thoughts about particles based on the data collected over time\textsuperscript{14}. 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, are:

\textsuperscript{14} Renstrom (1988) proposed six conceptions of matter before Johnson (1998a), but admitted that it was not an empirically determined sequence.
1. Model X – Continuous substance. Particle ideas have no meaning. Nothing that resembles having particles of any description is drawn.

2. Model A – Particles in the continuous substance. Particles are drawn, but the substance is said to be between the particles. The particles are additional to the substance. There can be varying degrees of ‘profile’ for the particles (weak or strong) and of association with the substance (none to close).

3. Model B – Particles are the substance, but with macroscopic character. Particles are drawn and are said to be the substance. There is nothing between the particles. Individual particles are seen as being of the same quality of the macroscopic sample – literally small bits of it.

4. Model C – Particles are the substance, properties of state are collective. Particles are drawn and are said to be the substance. The properties of a state are seen as collective properties of the particles (Johnson, 1998a, p. 399).

The classifications of students as having one of the four prescribed models coincided with four classroom units specifically designed to teach the concept of substance. Thus, the classifications serve as benchmarks for analyzing students’ spontaneous development of models for gases and particles. Curricular interventions often assume a generalized conceptual trajectory, and Johnson’s work provides data against which students’ natural engagement with concepts can be measured. Furthermore, perhaps more important than the specific developmental stages is the argument that a particle model, in a variety of accuracies, aides students in developing an understanding about substances (Papageorgiou & Johnson, 2005). The study reported in this paper will show that many of the findings in the literature are confirmed by the data, but that
some previously reported findings tend to oversimplify the ways in which students develop understanding of the science of air.

5.0 The study

5.1 Research questions

Considering that air is a collection of gases, we must also take into consideration the role of the particle model of matter, as it describes gases in terms of particles and their interactions. It is quite common for students in grades 5-8 to have had previous exposure to the term *molecules* and possibly even particles. In representing something that is unseen, such as a gas, the use of particle representations can be quite useful in explaining certain situations. Thus, as previously stated, while air is the topic on which this study focused, ideas about the particle model of matter were also explored, as this model helps to make sense of matter in the gaseous state for students at these ages.

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

- What conceptual aspects of air and a particle model of matter are students able to represent across different systems of external representation?
- How are students’ understandings of air and the particle nature of matter impacted by representing these concepts across multiple systems?
- How are representations produced through animations both similar and different from representations produced in other systems such as oral language, drawing, and building physical artifacts?
5.2 Research setting

The study took place in an urban K-8 public school in the Greater Boston Area. The school is considered a “neighborhood” school and a majority of the students live near the school grounds. The school body is a very diverse population with many students coming from different cultural, economic, ethnic, and racial backgrounds. This particular school hosts numerous educational research projects and students are accustomed to having adults other than their teachers work with them on a variety of projects. Participants in this study (described in greater detail below) are from the 8th grade, and were initially engaged in SAM Animation activities in the Fall of 2007. During this time, the entire class participated in a multi-week SAM Animation lesson where the students gained experience with the use of the software and different ways of making stop-motion animations. These activities purposefully ignored air, particle ideas, or other concepts (e.g., compression) used in the present research study.

5.3 Sample

Consent forms for the study were distributed to more than 100 8th grade students. Thirteen students returned consent and assent forms, and two students were chosen at random from these thirteen students as pilot cases. Interviews were carried out with each of these two students. The review of results from these two interviews led to some changes in the protocol for this study. The protocol reported in this paper reflects these changes. A sample of four students was chosen at random from the pool of participants whose parents had consented to their participation in the research study. These participants include (pseudonyms): Alison (14; 2), Amanda (13; 6), Fernando (14; 4), and Trish (13; 8).
5.4 Interview protocol

The study reported in this paper was designed to elicit multiple representations from students on the topic of air. These representations were produced after students were engaged in a science exploration\(^{15}\) for 5-10 minutes, described below. Morrison and Tversky’s (2001) "Conceptual Congruence Hypothesis" suggests 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). Additionally, because air is a gas, it has compressibility properties much different than liquids or solids, and we sought to make this capacity explicit in the demonstration. Thus, a demonstration showing change over time and compressibility was chosen for this study.

Figure 1. Syringes presented to the students in the study. The single syringe (left hand side of image) was presented to the student first, followed by the linked syringes (right hand side of image).

\(^{15}\) We purposefully choose the term “exploration” in place of “demonstration.” Demonstrations are generally performed such that the student (in this case) only observes manipulations performed by someone else. Some research (Crouch, Fagen, Callan, & Mazur, 2004; Roth, McRobbie, Lucas, & Boutonne, 1997; Shepardson, Moje, & Kennard-McClelland, 1994) suggests students will “see what they want to see” in the demonstration, and that is not the purpose of this particular study. By calling the activities “explorations” we highlight the fact that the student was given the opportunity to explore at his or her will. Whatever he or she observed was, thus, a result of his or her own actions, leading to what I believe could be a more meaningful engagement with the science topic.
5.4.1 Introduction and exploration

The exploration used in this study focused on air inside large (50 cubic-centiliter) syringes. Students were first asked what they knew about air without being presented a physical prop. After a brief conversation about these initial ideas, they were presented a single syringe and asked to explore it. Each participant spent a few moments describing the syringe and his or her familiarity with the device, and then they were presented with two syringes connected at the nozzles by a short piece of rubber tubing. With this device, as the plunger of one syringe is depressed, the plunger of the other syringe extends (see Figure 1). In addition, one can simultaneously depress both syringe plungers, noticeably changing the total internal volume of the systems by compressing the air inside the device. This device has been used by other researchers in investigations of students’ understanding of air pressure (deBerg, 1995; Séré, 1982; Tytler, 1998) and will be referred to as the "Linked-Syringe" exploration.

Participants were presented with the sealed-syringe exploration in three different 30-minute 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 interview utilizing the clinical interview method developed by Piaget (1929/1965) and later modified by Ginsburg (1997), among others (see also Brizuela, 1997; Duckworth, 1987, 1996). The clinical interview relies on the use of tasks to elicit student thinking. Ginsburg (1997) highlights 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 were conducted using the clinical interview method wherein the participant was
asked to produce representations in four different systems: oral language, drawing, stop-motion animations, and physical artifacts. The first session focused first on students’ production of a drawing, the second session focused on students’ construction of an animation, and the third session focused on their construction of a physical artifact. Students’ verbalizations (oral language) in response to the question “what do you know about air based on the linked-syringes?” were kept track of during all three sessions. There were approximately 2-3 days between each session for each individual participant.

5.4.2 Drawing - Prompt: "Could you show on this piece of paper what you know about air based on the linked syringes?"

A precedent for drawing as a system of representation in which students represent their ideas about science and mathematics is well established in the literature (Acher & Arcà, 2009; diSessa, 2004; Lehrer & Schauble, 2000; 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. After some moments talking about air and the devices (both the single syringe and the linked syringes), 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 a referent in two-dimensional drawings. Thus, for the purposes of this study it was reasonable to assume that students are able to, at least partially, represent their understanding of air through drawings. Students who did not spontaneously introduce a particle representation of air were prompted with a picture of a rectangular box with dots drawn inside (see Figure 3B) and were asked, “Another eighth grader showed air to me in this way, what do you think about this?” Typically,
students generated more than one drawing in the course of the session and a new sheet of paper was introduced each time they wished to produce a new drawing.

5.4.3 Student-Generated Animations - Prompt: "Can you make an animation showing what you know about air based on the linked syringes?"

In addition to two more widely used systems of representation—drawing and oral language—this study also used two less frequently used systems of representation. One of these is animations. In Martí and Pozo’s (2000) framework, they would view this representation as a hybrid system because it can include representations from other systems as well (e.g., drawings, text). The animations used in this study were generated with a tool called SAM Animation. SAM Animation is a piece of educational software developed by the Tufts University Center for Engineering Education and Outreach. 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 each (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, manipulatives, paper cut-outs, LEGO bricks, etc.). The user "snaps" the image they want 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 "play" the animation at a specific frame rate (measured in frames per second) that they prescribe. The result is a computerized movie, which

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16 Please see http://www.samanimation.com for more information on this software.
can be exported as a Quicktime™ file and shared with other students, teachers, and researchers. Church, Gravel, and Rogers (2008) have previously reported on success using this software with students in high school physics courses.

Students who participated in the study had been previously introduced to the use of SAM Animation software, as described above. In the second interview session, students were asked to generate an animation based on the above prompt. To facilitate this session, the students focused on making and manipulating the physical props for the movie while the interviewer controlled the computer interface, taking action only when instructed to by the student.

5.4.4 Physical Representations with Discussion - Prompt: "Can you build me something that might show what you know about air or some aspect of air based on the linked syringes?"

The second less frequently used system of representation that was used in this study is physical artifacts. Scientists regularly engage in designing experiments, building physical models, and manipulating materials that are tactile in nature. However, students have far fewer opportunities to explore scientific concepts 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 concepts – 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 very contradiction of making visible an invisible is what the study design capitalizes on; the relationship between a students ideas about air and their choices for objects to represent those ideas allows us another window into the relationship between externalization and conceptual understanding.

17 The same could be true with drawing.
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. Borrowing from that tradition and the known challenges of only relying on students’ verbalizations, physical objects and manipulatives were incorporated as the third system of representation in the final interview session. Similar to the Genevan tradition of task-based interviews, Bamberger (1991) describes 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 addresses the challenges of understanding students’ unspoken decisions and nonverbal representations of understanding 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) uses 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 their 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 asked participants to build something that would demonstrate some aspect of air based on the syringe exploration.

The materials included for this task were carefully selected to scaffold student’s explorations with the goal of developing a final artifact that students felt represented their understanding. By selecting materials that were easy to manipulate and aesthetically pleasing, students held a better chance of producing artifacts with which they felt comfortable. Instead of
giving students a limitless supply of materials, they were first asked to write a list of what materials they might use, and then they perused the provided materials (see Appendix A) to begin constructing the artifact.

5.5 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 drawings was collected and scanned, the animations were collected and remain in digital format (Quicktime™ movie files), and the physical artifacts were photographed. Each participant, then, has a portfolio of oral representations (also referred to as verbalizations), drawings, animations, and physical artifacts comprising the record for each case.

5.6 Analysis

The analysis of the data gathered from the four students in each of the three interview sessions was influenced heavily by Glaser and Strauss’s (1967) grounded theory approach as well as Lawrence-Lightfoot and Davis’s (1997) portraiture techniques. I acknowledge the strict assumptions and procedures associated with both qualitative research traditions, but reserve the right to adopt practices from both paradigms in the presentation of data collected in the reported study. As Charmaz (2006) contends, “We can use basic grounded theory guidelines with twenty-first century methodological assumptions and approaches” (p. 9). At its core, grounded theory (GT) is a process of theory-making through intensely thorough analysis of the data, in this case interview transcripts (Eaves, 2001; Glaser & Strauss, 1967). Grounded theory uses systematic, iterative categorizations of data to develop theoretical constructs that emerge from, for example,
interview data in a particular area of interest. “The primary purpose of GT, then, is to generate explanatory models of human social processes that are grounded in the data,” (Eaves, 2001, p. 655). Many would argue that any variation from the fundamental assumptions of this approach would violate the tenets of grounded theory and, thus, could not be considered GT research (Eaves, 2001; Wilson & Hutchinson, 1996). For example, a major tenet of GT is the use of theoretical sampling, which consists of gathering data from different groups to refine and exhaust potential categories of data (Eaves, 2001). Ignoring the processes of theoretical sampling violates the GT guidelines, but I do not believe that precludes the use of other GT guidelines in conducting sound qualitative research. The process of careful analysis of the data to generate codes, grouping the codes into categories, and returning to the data in an iterative fashion is a fruitful endeavor in exploratory research. This general, cyclical pattern of GT was employed in the present data analysis as means for unpacking the relationships between specific forms of representation and conceptual aspects of air and particles. Grounded theory guards against using existing literature to form categories or assumptions (Eaves, 2001; Charmaz, 2006; Glaser & Strauss, 1967). While the warning is acknowledged, I chose to combine elements of GT with existing literature on students’ ideas about air and particles in attempts to generate a coding scheme that would allow for the comparison of ideas across multiple representations. The literature was not used to form categories, but rather to confirm that the generated codes aligned with the existing literature on the topic. Overall, I employed a similar process to that of grounded theory, but chose to violate some GT guidelines in service of combining bodies of literature to make sense of students’ ideas – in essence, to ground these findings in the literature. The codes developed and refined were used to run quantitative statistics on the data collected. Coupled with the creation of codes were thick, rich descriptions of each participant’s trajectory through the
three-interview sequence. As Lawrence-Lightfoot and Davis (1997) argue, “portraiture is a method of qualitative research that blurs the boundaries of aesthetics and empiricism in an effort to capture the complexity, dynamics, and subtlety of human experience” (p. xv). The aim of this study is to discover the ways in which students externalize their ideas with different symbolic tools, thus, portraiture is a valuable means for attempting to present the complex relationships between ideas about air and particles and the ways in which these ideas are expressed. Therefore, descriptions of each participant’s journey through the interviews were generated to give the reader a sense of the challenges and successes the students faced in making sense of air and the particle model with particular symbolic supports.

5.6.1 Interview overviews

As mentioned before, this work is grounded in the qualitative clinical interview tradition where prolonged, multifaceted exposure with each participant allows for a thorough, in-depth analysis of the role of external representations in the development of science ideas. To accurately (and fairly) present the work of each student, overviews (similar to Lawrence-Lightfoot & Davis’s (1997) portraiture) of all three interview sessions were developed with examples from each student’s verbalizations and productions. The intent of these overviews was to: (a) characterize each student’s model for air and the particle model of matter, (b) describe the evolution of their ideas throughout each of the sessions, and (c) identify the role that external representations played in the construction of science understanding. While these accounts are lengthy and detailed, they provided valuable contextual details (an element of Portraiture; see Lawrence-Lightfoot & Davis, 1997) which assist considerations of more specific issues

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18 I purposefully avoid calling the overviews of each participant’s interview series portraiture, as the descriptions do not strictly meet the principles of the method as Lawrence-Lightfoot and Davis (1997) present. However, I direct the reader to their work to gain further perspectives on how this particular means of representing data is useful in the context of the present study.
addressed later in the results. In keeping with the qualitative tradition, validity and trustworthiness of the data hinge on the researcher and the reader understanding how each student constructed understanding and representations for air. I present two students’ overviews (those of Trish and Fernando) in the present analysis, as means for highlighting important aspects of the relationships between external representations and conceptual understanding. These descriptions are not meant to be comparative, but rather illustrative of trends in the data and potential areas of further investigation.

5.6.2 Development of a coding scheme

In Glaser and Strauss’s (1967) tradition, the transcribed interviews were coded line-by-line in an ad-hoc manner to assign specific utterances (small phrases or sentences comprising a complete unit of speech; see Bakhtin, 1986) to an initial set of ideas about air and the particle model. Patterns emerged from this initial coding scheme, and they were compared with the literature on students’ ideas about air and particles. A refined, yet still tentative, categorization of codes was generated based on the data and information obtained from the literature. Given this was not the first study on students’ ideas about air and particles, I felt it important to connect these findings to those which others have reported. The refined set of codes, consisting of the ad-hoc codes refined to better align with the literature, was then used to re-code the data and a further categorization of codes into a final collection was created. The final coding organized utterances into categories of ideas about air and the particle model, that were subjected to a quantitative analysis.

19 Using the existing literature to inform the creation of categories of responses is supported by Tomasello’s (1999) “ratchet effect,” whereby he claims that we must use elements and ideas developed by prior members of our cultures in order to avoid reinventing all the tools at our disposal.
For each interview session, the total number of utterances for all students per code was calculated. This allowed for comparisons across and within sessions (see Figure 2). For example, the frequencies allow us to see what ideas (i.e., codes) students tended to focus on in the interview sessions. Additionally, distributions of ideas across the sessions could also be computed to compare where (i.e., in what session) certain ideas tended to be addressed. This general frequency scheme provided for grouped analysis of particular codes, such as comparisons of students ideas about processes as opposed to their ideas about material-substance aspects of air.

Figure 2. Schematic showing codes used for both across-session and within-session comparisons in the quantitative analysis.

5.6.3 Categories: Process and material substance

Reviews of the data initially confirmed our hypothesis that certain conceptual aspects of air were represented more frequently in certain systems of representation. In an attempt to investigate this hypothesis, the codes were divided into two broad categories: (1) those pertaining to the material aspects of air and the particle nature of matter, and (2) the codes that related to process aspects of the context as well as air and particles (the groupings are found in Appendix B). This analysis provided for a comparison between the type of representation (oral language,
drawing, animation, or physical construction) and the frequency of ideas represented by each student and by the collective group of participants.

6.0 Results

It is important to recall that the overall number of participants in this interview study was small. The results for this study will be presented in two forms: (a) In-depth descriptions of two students’ (Trish and Fernando) trajectory through the sessions as a way to highlight many of the aspects of external representations that I am concerned with herein\(^\text{20}\); and (b) quantitative results for the four students.

6.1 Trish

Trish is a middle-class, white female student who is relatively quiet and is considered to “do well in school” by her teachers. The transcripts reveal her lack of confidence in many of her verbalizations (as is indicated by frequent “I don’t know” statements\(^\text{21}\)). However, her ideas about air and the particle model of matter became increasingly complex as the sessions proceeded. The story of Trish’s trajectory through three interview sessions highlights the interplay between developing an understanding of material substances while also (not necessarily simultaneously) making sense of processes, such as those represented in the linked syringe exploration.

\(^{20}\) While the stories are illustrative of the sample, similar to other single case studies (Confrey, 1991; Nemirovsky, 1994; Piaget, 1936/1977), I am not suggesting these results are generalizable in their current form.

\(^{21}\) Perhaps the “I don’t know” statements are also indicative of Trish giving herself time to contemplate and elaborate on an idea.
6.1.1 Interview and drawing: Focusing on air as a substance

In the first session, Trish offered that air is made of gases and that it exists everywhere, but she struggled to articulate specific aspects of air as a substance, “cause, you can’t see it…water is different because it’s like, actually there.” Trish’s efforts to describe air as a substance characterized her verbalizations and productions for the first session.

The single syringe provided Trish with a context for beginning to speak about air as a substance. She comfortably explained that there was air in the syringe and that depressing the plunger pushed the air out of the syringe. When presented with the linked syringes, Trish’s verbalizations about air were elaborated.

B: So, what do you think will happen when I push one of these [the syringe plungers] down?
T: This one [points to the opposite plunger] will go up.
[Trish depresses one plunger and the opposite plunger extends.]
B: Very good. So what do you think will happen if you pull this one up?
T: This might, this will come down.
B: OK…
T: Yeah…cause there’s air in here [syringe with plunger extended], and then when you push it, it goes and pushes that one.
B: What do you know about air from playing with this? Can you tell me?
T: Let’s see, it takes up space. At least like this, cause when you push it [syringe plunger that is extended] up then it [air] has to go over there cause, yeah…

Trish’s efforts to predict the results of the syringe exploration and her subsequent explanations helped her further consider conceptual aspects of air as a substance, in greater detail. While she was asked about two scenarios (pushing one syringe plunger down to extend the other, and extending one plunger to depress the opposite), her attention remained focused on describing air and how it moved as a quantity. Trish realized that the air inside the linked syringes was a consistent quantity (i.e., no air could be added or removed), and she used this information to describe what she saw. She argued that air moving from one syringe to the other needs a place to
go, so the opposite syringe plunger extends. Her explanation treats air in this context to be a continuous substance, rather than a more normative representation of air as a discrete collection of particles. Trish used this continuous model of air as a substance, however, her statements were quite vague and lacked a level of detail at this point in the session that would rapidly change as the session progressed.

While the focus of Trish’s attention during the interview portion of the session (before drawing was introduced) was on air as a substance, she questioned what would happen if she tried pressing both syringes at the same time. In exploring her question, she was exploring the process of compression, and she recognized that “the air compresses to fit in a smaller space.” However, her belief that air is a continuous substance appeared as a possible obstacle for generating an articulated verbal explanation for this process.

B: And how do you know that it’s a smaller space?  
T: Because you’re pushing both of them down, so it’s making it shorter.  
B: Gotcha, so this area is becoming smaller on both ends?  
T: Yeah.  
B: And the space in the tube, that’s not changing, or is it?  
T: [Shakes head no.]  
B: So when you say…what’s happening, do you think, to the air that allows it to get smaller? You said compression, but what do you think that really means?  
T: Um…  
B: How could you describe it?  
T: I guess, I don’t know. 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.

While Trish was comfortable talking about the process of compression, her (presumably) continuous model for air did not provide her with the resources necessary to explain such a process; a continuous representation of air does not easily provide for a way of talking about compression. It was not until she began to draw her ideas that her continuous representation was transformed into something more generative.
Trish was asked to put something on paper to explain what she had observed, and she drew linked syringes with scribbled lines representing air inside the syringes (see Figure 3). Trish made explicit the stipulation that “you need a contained space” by writing these words alongside her drawing, further evidence of her interest in the contained quantity of air in the system.

![Figure 3. Trish’s first drawing depicting the linked syringe case.](image1)

Trish was asked to represent air in a container and she produced a drawing with continuous lines representing air (Figure 4A). Trish’s thinking was probed when the interviewer presented her with a particle representation of air and asked, “Another 8th grader drew air this way, what do you think about that?” (Figure 4B). Trish paused and then began to contemplate the particle (Figure 4B) version. She replied, “I guess, because, they could…but I think it would fill the whole thing, well, I don’t know. Cause these [dots on the page] could be like air molecules, or something, I don’t know.” Trish initially questioned the particle representation (i.e., Figure 4B) but began incorporating it into her productions. When asked to recreate her drawing (see Figure 5), the revision included dots on paper as representations of air. Trish went as far as to show a different spacing of dots to represent compression. She offered, “If you pushed this, both of the ends down like this, then there would be like more of them...So, they
would like squish together, so there would be a lot more in one space.” Considering air to be a collection of particles as opposed to one continuous substance appears to have proved generative for Trish. Regarding air as made of molecules encouraged Trish to think of a variety of ways in

![Figure 5](image)

Figure 5. Trish’s recreated linked-syringe drawing including dots representing “air molecules”.

which these particles could be spaced depending on whether they were being “squished.” With that said, simply representing air as particles versus a continuous substance does not provide answers to other problems with the syringe explorations, such as why the plungers can only be compressed to a certain point. When explaining this scenario Trish stated, “Because they’re…like, entirely squished together, so there would be a lot more in one space.” It is unclear what substance air might become when the gas particles are “entirely squished together.” Regardless, Trish was developing her understanding of air. Both her interactions with the interviewer’s representation of dots on paper as particles, and the process of generating her own representations appears to have helped her gain clarity in her explanation of compression. Even if her verbalizations were non-normative (i.e., “entirely squished together”), the consideration she gave to particles and their interaction shows some change in her thinking about air as a substance. Trish’s development of a richer representation of the material substance aspects of air is further evidenced by her continued exploration of compression in the syringes.
B: When we let go of this [air in syringes being compressed by pressing both plungers],
why do you think it moves back up?
T: Cause they’re spread out?
B: So they want to be spread out?
T: Yeah…
B: Why do you think that is?
T:…
B: Got any ideas?
T: Um…because…I don’t know. Um…I don’t know. I guess that, like, the air that we
breath and stuff, or like the air that’s everywhere is not compressed, but like, I don’t
know, it’s just…I don’t know, it wants to be spread out.

Her commitment to the term “spread out” indicated two points: (1) she was developing an
understanding and a representation for how particles may be organized, and (2) her
understanding of the material substance properties of air provides her with resources to
contemplate process aspects at a deeper level. While Trish offered no explanation for why
particles “want to be spread out,” the utterance demonstrates that her attention has shifted to
considering not only air as particles, but how particles may interact with each other. Trish’s
attention to material substance aspects of air and her initial representations of a particle model
are clear trends in this first interview and drawing session. She talked about process topics, but
this only led to further engagement with material substance ideas. In the animation session, we
see Trish begin to build on the particle representations she constructed in this first session as
means for thinking about processes.

6.1.2 Animation: Making sense of process

When Trish was asked to make a stop-motion animation about air based on the linked
syringes, she immediately attended to the problem of representing “air molecules” and her
understanding of compression, perhaps picking up from her last set of concerns from the
previous drawing session. She settled on small pieces of paper as representations of air
molecules moving inside an outline of linked syringes (see Figures 6 and 7). The process of generating the comparison between the compression states prompted her to say, “It’s like how it

![Figure 6. Screen-shot of Trish’s animation showing paper dots as air molecules “spread out” in the linked-syringes.](image)

![Figure 7. Screen-shot of Trish’s animation showing air molecules “getting squished together”.](image)

would be if you didn’t touch it, and they’re, like, spread out.” When both plungers are pressed, she commented that the air molecules are “getting squished together” (see Figure 7). Both of these statements were carried over from the drawing session, where she appeared to have honed her representations of air as particles, prompted initially by the interviewer’s intervention. With some understanding of how particles might interact and how differences in air particle spacing can represent different levels of pressure, Trish constructed a representation of force transfer through air that was remarkably sophisticated.

While generating the animation, Trish took great care to move all the air particles (represented as paper dots) together along the device. That is, when representing the case where one plunger is depressed and the other extends, she moved all the air particles in succession along the image. Implicit in this representation is a potential mechanism for transferring forces in a closed system – another process idea. In Trish’s animation, molecules move toward those
closest to them, which in turn move toward the next proximal particles, and so forth to transfer
the force. Such a mechanism relates to the Newtonian model involving attraction and repulsion
forces. A more current view is that a force applied to a gas in such a situation results in collisions
between particles being propagated in the direction of the force (because the gas is in a contained
space). Regardless of whether Trish’s representation was normative, generating this animation
positioned Trish to consider the interaction between particles, including force transfer. For
example, when asked why one feels resistance on the plungers if they are both being depressed,
she argued that there was “too much air” in the system. From her point of view, one could
depress the plungers further, if there was less air in the system to be compressed. Implicit in her
statement is a belief in a limit regarding how much air can be compressed. She commented
earlier about compression decreasing the space between molecules, thus, she seems to be
contemplating particle interactions. Rather than a clear articulation of pressure and force,
however, her animation and explanation illustrate a movement toward thinking in greater detail
about the interaction between particles in different scenarios.

In summary, there was a shift in conceptual focus from Trish’s first to second session. The oral and drawing session yielded a larger number of utterances (42 material-substance utterances as compared with 27 total process utterances) concerning the material substance nature of air. That session evolved into utterances and productions of particles and particle spacing, but mostly remaining in what we could consider to be a material substance domain. However, in the animation session, when asked to consider movement, compression, and change over time, Trish was able to reproduce the particle representations she generated in the first session to begin addressing issues of process. Her animation showed how particles under pressure interact in the syringe system. It also included a representation of a force transfer
mechanism between the particles of air. Thus, for Trish, the animation session appeared better suited for her to explore process ideas, while material substance ideas were more frequent (42 compared to 27 process utterances) during the oral language and drawing session. This is a recurrent theme that will be addressed in detail below. Spending time contemplating what air consists of, how those elements interact, and how to represent those interactions led Trish to begin questioning and further verbalizing her assumptions about air during the physical construction task.

6.1.3 Physical construction: Particles and processes

Confronted with the request of building something to help describe properties of air, Trish opted to re-represent the linked syringe device.

T: So we have to figure out a way to show the air molecules, I don't know what we could use.
B: What did we use in the animation?
T: Paper...dots. But they have to be able to, like, move around and stuff. And, it has be something that you can, like, pick up.
B: What do you mean, you can pick up?
T: Like, something, like, not like a paper.
B: Right, ok...so...
T: Alright...I guess we could use paper for the air molecules, kind of. But then we have to be able to show this thingy [the syringe].
B: So, you were saying you think you could use paper, like little paper dots, like you did in the animation to show air...
T: [Nods head yes.]
B: What other kinds of stuff would help us show air?
T: Um...but we're going to have to be able to show, like, all the stuff that we did, like, when you push down on both sides of it, or when you push on one side, so they have to be able to move around. But, like, we can't, like, they would just all, like, fall, I don't know, like, it wouldn't work.
B: What do you mean they would all like fall?
T: Like, if you were to make one of these [syringe] and then put paper in it as the dots, they wouldn't, like, do what you wanted, because they're not air.
B: Ok...
T: So...
B: But you think you'd want to try and make something that would show the air molecules and how they interact or how they move through the system?\(^{22}\)

T: How they move through the system, and, like, like, become more, like, dense when they're squished together.

Trish was primarily concerned with finding a physical representation of an air molecule. The above episode illustrates the challenge she had in finding a physical material or element that would mimic the qualities of an air molecule, as she understood them. At this point, we do not know exactly how Trish would represent an air molecule. Perhaps her struggles to find the right material are indicative of a lack of clarity in her individual, idiosyncratic representations of air. Trish’s discomfort demonstrates the challenge of externally representing an unseen. But that challenge is likely confounded by working within a hybrid system such as physical construction, which is an unfamiliar way of externalizing understanding for most students. She likely has little experience representing an unseen entity, such as a gas particle, using raw construction materials. Trish’s question about how to capture the idea of an air particle in a physical instantiation is part of the challenge of externalizing an unseen idea in an unfamiliar way.

This challenge does not mean we should shy away from these situations; on the contrary, the complexity underlying the situation could bring about important conceptual developments; this process could result in the individual engaging in the problem and content at a deeper level, as Trish, for instance, must confront her conceptions of air particles, regardless of whether she is able to articulate these assumptions. Her statement, “They wouldn't, like, do what you wanted, because they're not air,” provides the researcher with a window into her present representation for air molecules. Some aspect of how small pieces of paper behave is counter to her understanding of air molecules, and the process of trying to externalize her understanding in this

\(^{22}\) In the first interview session, Trish had been introduced to the syringes as a “system”, and was thus familiar with the term in reference to the device during this exchange.
physical system allows us a glimpse at the assumptions inherent in her understanding. Additionally, this contradiction between how air is being shown (i.e., the external representation she has produced) and how air “should be shown” (in Trish’s opinion) also allows her to make explicit her understandings about air; making this contradiction explicit allows Trish to reflect on her understandings.

Eventually, Trish decided on small, stainless steel ball bearings as a representation for air, but immediately expressed her discomfort and reservations about representing the particles in this manner. She said, “They wouldn’t, like, move the same as air molecules, I don’t think…they’re like things, they’re not like…” at which point she struggled to verbalize her hesitations about the ball bearings. Earlier, Trish had described air molecules as being able to “float,” thus her reservation about the metal ball bearings could stem from a desire to represent the same behavior. She seemed genuinely uneasy because she continued to describe air as “something,” but a different sort of something than the ball bearings. Trish’s continued challenges in verbalizing this difference may suggest that oral language (and possible physical artifacts are not either) is not the most comfortable form for her to externalize these ideas. We can postulate that engaging in the exercise of finding a physical, observable representation of air molecules may help Trish develop her understanding of an air molecule; time spent exploring possible representations for a molecule in a physical system could help her to construct an oral representation of her understanding. While further evidence is necessary to confirm or deny this hypothesis, it is clear that Trish was focused on material substance aspects of air during the first segment of the construction session. However, once a representation for air was chosen, her focus began to shift toward representing how they (i.e., air molecules) move through the device.
Trish built her device (see Figure 8), and it was a single syringe representation containing ball bearings meant to represent air molecules. With the device built, Trish began contemplating some of the processes that she explored in the earlier sessions, namely how she achieved compression with the two syringes. The ball bearings in her device tended to line up in an ordered configuration, which again made Trish uncomfortable. The ordered, compact nature of ball bearings in a line was in conflict with her belief that “when you push down on both sides it needs space to, like, get squished together.” The lack of visible space between the air molecule representations contradicted her understanding of compression. Instead of altering her explanation of how air was compressed in the linked syringes, she chose to point out the limitations of the model she had built while verbalizing her understanding.

B: What do you think they [air particles] look like in here [points to the tube]? Do you have any idea what kind of arrangement they would be in? Do you think they'd all be in a line, would they all be ever, or would it be kind of random, what do you think?
T: I think it would be kind of random.
B: How come?
T: Because, um, I don't know if they're all, like, the same shape or whatever. They're just like...cause they're definitely not like these balls.
B: They're not like the, well, you already said that the balls are heavier, but what else? How else are they different?
T: Um...these, like, go down to one side and air molecules, like, float.
B: Ah, ok. So the air molecules, what's another way you could say that they float? Like another way to describe that.
T: They're...um, in the air, I guess. Like, I mean, like, they don't, like... they... like...gravity doesn't change them. It doesn't make them, like, go down or whatever.
B: Ok, it doesn't make them go down. Let's think about it this way, if I've got air and this is one space in here [pointing to the linked syringe device], does air fill the whole space or is it only in part of the space?
T: Yeah, it fills the whole space.
B: Ok.
T: But, spread out.

This exchange illustrates how the process of explaining how a representation is not like the situation in question turned out to be an interesting and valuable aspect of constructing physical artifacts. Highlighting the aspects of a system that are at odds with one’s ideas not only compels the student to question those assumptions but also provides the researcher with an interesting window into what aspects of air are most interesting or important for the student. Trish appears to hold an intriguing belief in a relationship between gravity and air molecules. Likely, she believes that gravity pulls things toward the earth, and air molecules somehow defy the force of gravity. While these are non-normative ideas, the process of representing understanding in this physical, hybrid system elicits aspects of thought that may otherwise remain unnoticed. In this session, Trish began contemplating the problem of representing the material substance aspects of air. As she constructed the device and used it to explain her understanding, her attention shifted toward the processes inherent in the linked syringe problem. In the prior sessions, she appeared to focus on either material substance ideas or process ideas, but rarely were they simultaneously considered. In this third and final session, she begins jointly consider her representations for air as a substance with her understanding of the processes air goes through. This progression is intriguing and revealing and will be discussed in more detail later on.
6.1.4 Trish: Summary

Trish’s experience throughout the three interview sessions provides evidence for the interplay between systems of representation and her understanding of conceptual aspects of air. She began with an emphasis on the material substance aspects of air during the oral language and drawing session. Initially representing air as a continuous substance, Trish slowly transitioned into a particulate representation once it was introduced to her by the interviewer in drawing form. Her attempts to make sense of how the device worked required an understanding of the material substance. Trish’s continuous model gradually transitioned into a particle model (due, in part, we assume, to the introduction of this idea by the interviewer), which led to her subsequent contemplation of the processes involved in the linked syringe exploration. Whether the limitations of a continuous model were evident to her is unclear, but regardless, representing air as particles proved more generative for Trish, as she adopted this representation in later sessions.

The particle model carried over into the animation session, where Trish used particles to represent the processes of force transfer and compression. One could argue that she spent the first session constructing a representation for air as a substance, and in the animation session she began to consider process ideas involving particles of air. Both sessions prepared her for the physical construction task, where she further related the ideas and representations she produced in the first two sessions. Trish appeared to strike a balance between material substance and process ideas in the construction session. It was during this interview that she also pushed the limits of her understanding of the linked syringe case. Her trajectory suggests a measure of order effect in how the sessions were deployed; however, the connections between systems of representation and conceptual aspects of air remain intriguing.
6.2 Fernando

Fernando is an 8th grade student who is a self-proclaimed “science lover” and a naturally inquisitive young man of Indian heritage. He is quite articulate and enjoys engaging in discussions using rather academic language. Over three sessions with Fernando, he demonstrates how externalizing ideas can aide a student in synthesizing a multitude of seemingly disconnected ideas about air. Fernando uttered many terms and phrases taken from school science (i.e., canonical statements about air and particles, such as, “Molecules have kinetic energy”); however, he was challenged by the task of using these ideas to make sense of the syringe exploration. Over the course of the sessions, he was able to investigate various aspects of air and particle interaction through multiple systems of representation that eventually yielded a richer, more sophisticated understanding. Fernando’s case further illustrates the interplay between external representations and conceptual development.

6.2.1 Interview and Drawing: Discovering a particle model

In the first session, Fernando initially attended to the unseen nature of air. However, instead of discussing air as a material substance, he began talking about “seeing” air through other things, such as wind blowing the leaves on trees. He argued that air is made of oxygen, but that “we breath oxygen, which is different from air…air is like something like a force…oxygen is not like, I mean, it can be moving in and out of things, but it’s not really moving things.” Fernando’s initial struggles with defining air can be interpreted as well-documented challenges (Johnson, 1998) that students have differentiating between mixtures and pure substances. Air is a mixture that contains a number of pure substances such as oxygen, which could be causing problems for Fernando. However, his later statements regarding the fluid properties of air
suggest that his primary challenge is to distinguish between continuous versus particulate representations. Fernando’s descriptions of the syringe case were mostly verbalized observations, and his explanations focused on quantities of air moving through the device. When asked about compression, he said:

“[The air inside the system] is becoming dense, so it’s being, it’s harder to push… the space between the two syringes is becoming denser… it’s becoming smaller… it’s becoming a smaller space so the water [unclear as to why he said water instead of air] is just compressing together, it’s pooling together and it’s becoming harder to press down.”

These first verbalizations focus on the bulk properties of air, such as changes in volume, but Fernando began to include particle ideas when asked to put something on paper.

Figure 9. Fernando’s first drawing showing “Air flow”.

Figure 10. Fernando’s second drawing, incorporating particle representations, which includes the interviewer’s representation of air as dots in a box, shown in the upper left of the drawing.

Fernando’s first drawing described “air flows” and referenced trees moving as evidence of air’s existence (see Figure 9); his initial drawing productions focused on air as a substance in continuous form. However, when he was prompted to think about a particle representation of air
(introduced through drawing, as with Trish), he began reciting some canonical statements about molecules: “molecules move”, “they generate heat”, and “everything is made of molecules.”

Fernando was explicitly asked if air was made of molecules, and he responded, “Yeah, air should be made of molecules.” These utterances suggest that he is comfortable using “token explanations” (Perkins & Grotzer, 2005) about the existence of molecules (i.e., classic definitions of molecules moving and generating heat). But Fernando finished his description by saying air “should” be made of molecules, which is suggestive of his doubts about a particle model of air. Fernando continued exploring particle ideas by comparing solids and liquids with air (i.e., a gas). In doing so, he was able to produce particle representations of the three states of matter (see Figure 10). Even if Fernando was comfortable talking generally about matter as particles, even in different states, his ability to apply those ideas to the syringe context was lacking. I asked him to connect the ideas he drew to the linked syringes and he attended to the situation where the syringes compressed the air in the system. He offered:

“So, as you're pushing down, the molecules are becoming denser, so that there's really this...I mean, if I were to punch this table, it would hurt. So it's sort of, kind of like that. You know, these little plungers are like pushing the air, they're forcing it together. They're just making it come together, because as gas, you know...like take oxygen in the atmosphere, there is so many gases just spread out, you know? They're not really being touched. Like, as you fall, you can feel the air, kind of pushing through this kind of invisible web, and so, as you're pushing down on these, you're taking all these molecules and you're making them denser. They're not becoming physical, but you can feel that there's this force, that there's this compression of molecules.”

His statement is laced with a variety of both continuous and particle ideas, which is suggestive of Fernando’s struggles representing his model of air (either continuous or particle-based, or both) verbally. The process of drawing along with giving verbal explanations appeared to help him organize his ideas about particles.
Fernando continued to provide both continuous and particle ideas as the compression case was further explored in an additional drawing (see Figure 11). Fernando’s drawing demonstrated the difference between when he was pressing both syringes down at the same time (left-hand image) and when he was not exerting a force (right-hand image).

Figure 11. Fernando’s drawing representing his ideas for the compression case involving particles of air.

His verbal explanation of these two situations was as follows:

B: So, how do you think the molecules would look in those two situations?
F: So...you're not really tampering, so the molecules are still spread out, but as you're forcing...they're kind of moving, and coming together.
B: So they're moving and they're coming together? It looks more compact
F: So there's this force...down here...and then...
B: What do you mean by "there is"?
F: Like, there is, you know, when you push down on these, you have the limit, right? It feels like a wall.
B: What do you think is pushing back on you? Why does it feel like a wall?
F: Because the molecules, because molecules have energy, kinetic energy, right? I'm getting that right?
B: Yeah
F: Ah, so, I guess because of the energy, it's stronger...cause it's moving faster than you are. Like, as, as you're pushing down, you're using your energy, your physical energy. But it has its energy of its own. So I guess it's, you know, it's conflicting...these plungers...
Fernando expressed, verbally, some token statements about molecules, but was challenged by the task of incorporating these into an explanation of the compressed syringe scenario. He invented the idea of a “force” or “wall” that is stopping the syringe plungers from being depressed any further, and he represented this idea on paper with a squiggly line across the top of the molecules. In Fernando’s explanation, he mentioned that the molecules are “coming together” but then resorted to kinetic energy as an explanation for the force he felt when trying to press both syringe plungers simultaneously. His drawing includes short lines behind each particle, which are interpreted as representations for motion. In the case of the untouched syringe (with no force applied to the plunger), he explained that the molecules are spread out and includes no explicit representation of motion. From this third drawing, Fernando appeared to be adopting a particle representation, at least to a certain degree.

Both Fernando’s verbalizations and drawings show his willingness to use the idea of molecules or particles in his explanations of air. He offered some explanation of the process of air becoming more compressed; however, these explanations hinged on how to represent the material substance aspects of air. His third drawing shows a rather advanced understanding of particles in motion (i.e., intrinsic motion). However, he appears to believe this is only the case when the air is being compressed; kinetic energy is his reason for why there is a limit to how much one can depress the syringe plungers. Thus, Fernando, through both oral language and drawing, invented a representation that incorporates school-science phrases into an explanation of the syringe context. Interestingly, the progress shown in this session towards a particle representation.

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23 Kinetic theory states that particles are in intrinsic motion, thus having kinetic energy. Fernando’s explanation could be seen as a highly advanced understanding of kinetic theory and particle collisions, however, his later statements suggest that this is not likely the case. Rather, he attempted to include a canonical idea in his explanation of the compression case.
representation of air was not spontaneously carried over into the animation session, where Fernando returned to a continuous representation of air.

6.2.2 Animation: Material substance and process collide

Fernando used the actual linked syringes device for describing how quantities of air move through the system in his animation. He said he wanted to represent the “whole air compressing and stopping,” as the basis for his animation. He added, “I was just thinking, like, does the air stop here [points to the nozzle of the syringe] or does it stop here [points to the midpoint of the connecting tube]?” One interpretation of Fernando’s intent is that he wished to represent the air in the syringes as two separate quantities that interact to cause the “wall” he mentioned in the first session. Instead of engaging with particle ideas, as he did at the end of the first session, these statements suggest a representation of two quantities of air, further demonstrated in his animation.

The first part of Fernando’s stop-motion animation (see Figure 12) focused on how air moved back and forth between the syringes. He used red lines with arrows going in one direction and green lines with arrows going in the other direction to represent two quantities of air, or “flows” as he labeled them. Written next to each syringe are the words “air passing”. The inclusion of such markings in the animation supports the argument that Fernando has reverted to
a continuous representation of air, and this may be indicative of the level of commitment he had to the particle ideas in the first session. If you recall, he tended to mention token phrases about molecular motion without expanding upon those ideas. It is my contention that he did not fully grasp how a particle representation was useful in explaining processes, and thus returned to using the continuous language and representations with which he may have been more comfortable.

When I asked Fernando to verbally explain his animation, two interesting exchanges emerged that highlight aspects of his understanding:

B: Ok, so tell me a little bit about the two, ah, different colors of air arrows.
F: Well, um, I wanted to show that, I mean, I thought of using the same colors at first, but then I said because there are two tubes, syringes, I wanted to show the difference so that whoever was watching the movie could show that it's the same air, but it's moving in two different ways. And these two different colors, um, kind of give a different, it differentiates, like, the flow.
B: Ok
F: From one tube to the other. And, yeah...
B: So you're showing that air passes from one to the other and back and forth again?
F: Right.
B: That air can pass to both tubes?
F: Hmm, hmm.
B: Cool, ok, so we get to the bottom here. So here's the second "half" if you will, the second "act" of your movie. Um, so talk to me a little bit about what you were trying to show here?

F: Um, that's when I wanted to show that there is a limit on how much you can, how much air can flow through. Like, there's...there's that point where if you try to push it down at the same time, you know, what would happen? And why that happens. So, you know, it kind of shows that, you know, there's this barrier right here. I just wanted to represent, like, this invisible barrier, like, and, basically I used that color scheme which was, you know, like, one color represented air coming from this side and one color represented air coming from this side, and they're kind of compressing like that [gestures two hands coming together, fingers moving past each other as if integrating]. Molecules are compressing, it's kind of like this little wall, and, yeah. And that little diagram is to represent what's happening between these tubes.

B: Ok, so talk to me about, if the wall is here at the bottom of this tube, how is that stopping your hand from being able to press down any more?

F: So, once the barrier is there, what happens is that....I should actually, shoot. Anyway...

B: Go ahead, you can explain it to me now

F: Yeah, um. What happens is that once it makes that barrier, and you're still pressing air, you see? So you have the little barrier, the air's pressing, it kind of, like, as it's compressing, it...it...it becomes denser at these two ends, so you can't press any further.

B: Ok, so does it become more dense here [points to middle of tube] or is it the same, or is it the same density....

F: I guess like, I wanted to envision, like, there's this point where it happens. And kind of, you know, sets that reaction.

In the first exchange, Fernando claimed that he wanted to show the viewer that it was “the same air, but it was moving in two different ways.” The use of two different colors served as a means for highlighting the two different “flows”, as he called them. While he originally claimed it is all “the same air”, his representation of two distinct quantities suggests that he may have been simultaneously considering two ways of thinking about air. The second half of his animation supports this idea (see Figure 13), because he shows two quantities interacting to form the “barrier” or “wall”. He later added that, “there’s a point where it just slams together.” From these examples, we have the impression that Fernando is wedded to the concept of two continuous quantities interacting with each other. However, he also mentioned molecules compressing and even created a gesture to the effect of parts (i.e., fingers) interacting. This may be indicative of
Fernando’s attempts to combine particle ideas with his continuous representations, but probing his thinking about particles further reveals some confusion on this point.

I asked Fernando to recall our earlier conversation about particles and to consider the compression case in regards to molecules. I asked what he thought was happening when we compressed the air inside the syringes, and the following exchange occurred:

F: Particles are becoming denser
B: Becoming denser, describe that a little bit more.
F: Like, well, they’re becoming denser, they’re getting closer.
B: They’re getting closer.
F: Yeah.
B: So what’s between them right now? What is between them…
F: I guess that’s what the wall is.
B: Say that again, that’s what the wall…
F: I meant, I guess that’s what the wall is…because the particles are, are like forming together.

Fernando touched on a complex issue, which is the concept of air particles becoming closer together when being compressed. However, his understanding is unstable, because he quickly uses that idea to conjure up an explanation for the particles “forming together” to form the wall or barrier he previously mentioned. Fernando’s understanding of air appears to have developed, even if only slightly, as a result of thinking more explicitly about the processes involved in the linked syringes. While he still may hold largely continuous representations of air, he has begun to consider ways in which particles could explain what he experienced.

In this session, his attention was mainly focused on process ideas, such as air flowing through the system and the creation of this “barrier” or “wall” to explain resistance in the plungers. He attended to material substance aspects of air toward the end of the session, but these ideas were unstable and weak. A shift in attention toward process ideas in the animation session occurred for Fernando, as had occurred for Trish. However, Fernando’s use of particle ideas was
must more infrequent in his explanations of the processes observed during the syringe exploration.

6.2.3 Physical Construction: Toward a particle model

Fernando began considering how to construct a physical representation by exploring a balloon pump and a sports-ball pump that were in the kit of materials for the third session. After quickly realizing how a pump is different from a syringe (i.e., a pump houses a unidirectional valve), he spontaneously recalled the conversation about particles. “I’m remembering when we were talking about, um, how like, could use these as little particles [holds up a bag of ball bearings]…Now maybe if I could just put some into the tube, and when we push down from one end to the other, it kind of represents the air and what’s happening inside.” His recollection of

Figure 14. Fernando’s physical construction explaining what he knew about air

our particle discussions was perhaps sparked by finding ball bearings amongst the available materials, and he began to think of how ball bearings could represent some aspect of air. This was his first unprompted use of the particle idea. After some time spent exploring the materials, Fernando attached a transparent section of tubing to the end of the balloon pump with a stopper placed at the other end of the tubing (see Figure 14). In this instance, since there was a relatively
small volume of air in the system (small amount in the pump and an even smaller amount in the thin-diameter tube) when he pressed on the pump the resistant force was immediately evident. This appeared to intrigue Fernando, and he said, “Um, well…yeah…there’s like a…trying to find a word for it…kind of like a, like a wall or something, like what I was saying earlier with the syringes.” Searching for a way to verbalize this force he felt on the pump, Fernando again used his concept of a “wall” or “barrier” to make sense of the situation. He placed ball bearings into the tube and recreated this compressed situation, finding amazement in the fact that the ball bearings were able to roll around inside what he thought was a “compressed” situation. He stated, “It just shows that there’s no force…like, there’s no, there’s no, like, since the air’s not pumping through it…the air has no direction in which to move.” Recall Fernando’s original descriptions of air as a force and how a movement indicates the presence of air. In this situation, because air is not moving through the tube, he does not believe there is “enough air” to generate a force against the freely-moving ball bearings. Fernando’s description of the barrier in the animation session was dependent on quantities of air colliding and “forming together.” Perhaps he believed that compressed air emulated a solid or a liquid, in which other objects (e.g., ball bearings) would not be able to pass through easily. While he was representing particles within his production, he appears to retain some tendency to consider air as a continuous or fluid quantity. However, in continuing with this line of discussion, Fernando began thinking more about how particles may interact as opposed to particles existing within a continuous quantity of air.

Fernando was asked to describe his surprise observing ball bearings moving through compressed air:

B: So how come that is? How come when I have pretty compressed air molecules I can move something through it?
F: I mean it's air. I mean, say if you were in a tight, cramped space and you still had some, you had air in there. You can barely move around, but that's just because of space. The particles that are dense here [points to the tube] aren't as dense as what's...[knocks on table]. There's a level of density. Right...pressure. So, I mean...

B: What do you mean, right, pressure?

F: Um, I'm using the term pressure because, you know, pressure involves, like, how things can move around...like in a...like how tightly packed something is. There's a lot more, um, pressure in...I guess, a desk, in the particles that make up a desk, more than what makes up air.

Fernando’s search for phrases to explain a density gradient indicates a desire for more clarity in his verbalizations. Rather than simply stating that something is “more dense”, as he had previously done, Fernando contemplated the ways in which density could vary. He introduced the word pressure and tried to relate that to the density of a material substance, such as the wood (i.e., the material from which the table was made). While we must take caution not to over-interpret this statement, I offer it as evidence of Fernando beginning to think about particles, particle spacing, and the differences between different states of particle spacing as they pertain to matter in the gaseous state. The phrase “how tightly packed something is” suggests a shift where particles are not thought of independently from air, but rather as the substance itself. I would not argue that Fernando has reached a normative understanding of matter in the gaseous state, but it appears that through the process of externally representing air concepts and the introduction of the particle model (in a basic form), Fernando’s understanding became more sophisticated, as is evidenced by the incorporation particles in his explanations of air.

6.2.4 Fernando: Summary

Transitioning from a continuous representation to thinking about matter as particles is not an instantaneous process (Johnson, 1998). For Fernando, we see a slow, successive adoption of particle ideas as he begun to make sense of the linked syringe device. Beginning with a focus on
material substance aspects of air, he transitioned toward pondering process ideas while generating the animation. Attempting to make sense of the processes led him to revisit his representation of air and to begin adopting particle ideas. In his final session, combining his material substance understanding with a desire to physically represent the process of compression in the syringes led Fernando toward the development of more advanced particle understandings. Whereas he focused on continuous representations of air in the earlier sessions, by the final interview he was contemplating particle spacing in cases of compression, which is indicative of this shift toward a more complex understanding. Like Trish, the story of Fernando’s conceptual evolution throughout the three sessions shows the interplay of external representations with concepts such as air. Through a process of engaging in an exploration of a device, interpreting provided representations (i.e., air as dots on a page), and externalizing understanding, I believe students can spontaneously develop more complex, coherent explanations for physical phenomena.

6.2 Quantitative analysis

Students have been shown to harbor different conceptions about material and process aspects of natural phenomena (Chi, 1992; Slotta, Chi, & Joram, 1995). Thinking about what something is as compared with how something changes requires different cognitive resources for students. This categorization can be applied to air, as there are decidedly different aspects of air as a material and the processes air undergoes. It is reasonable to suspect that a relationship exists between systems of representation and conceptual aspects of phenomena, such as with air (see Zhang, 1997; Zhang & Norman, 1994). The analysis presented here attempts to differentiate
between the systems of representation employed in this study and the characteristics of air that students tended to highlight within each system.

The data were coded as described earlier, and two categories of codes were generated based on Chi’s (1992; Slotta, Chi, & Joram, 1995) work on material-substance and process aspects of science phenomena\textsuperscript{24}. Based on these categories, the data were organized according to these two broad conceptual aspects of air (i.e., material substance or process), and Chi-squared tests were performed to analyze the observed outcomes versus expected outcomes. In this case, the null hypothesis was that no difference in the frequency of material substance as compared with process ideas would exist across or within the systems of representation employed. The interviews were divided into four sessions, whereby the interview (before the student was allowed to draw), drawing, animation, and physical construction are all treated as four separate sessions. This distinction was created to compare what ideas students attended to while attempting to externalize their understanding using the four different systems of representation.

Table 1. Utterance\textsuperscript{25} frequencies within session/type of representation.

<table>
<thead>
<tr>
<th></th>
<th>Interview</th>
<th>Drawing</th>
<th>Animation</th>
<th>Physical</th>
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<td>78</td>
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<td>10.714**</td>
<td>8.627**</td>
<td>0.641</td>
<td>2.348</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, *** p < 0.001

\textsuperscript{24} It should be noted that using Chi’s (1992) categorization of material-substance and process ideas does not presuppose an adherence to her theory of ontological categories and conceptual change. This issue is discussed in further detail in the Discussion.

\textsuperscript{25} The term “utterance” is defined in the description of methods (see Section 5.6.2)
Table 1 reports the total frequencies of material substance and process ideas uttered by all students for each of the four session categories listed. The total number of material-substance utterances in the interview and drawing session was significantly higher than expected when compared to process ideas. While not significant, the number of process ideas uttered in the animation sessions was higher than the number of material-substance ideas. Lastly, material-substance ideas appeared to dominate process ideas during the physical representation session although the difference was smaller than in the oral and drawing sessions. This is evidenced by Trish’s focused attention on selecting an appropriate representation for an air molecule – in her case, the metal ball bearing.

Table 2 compares the frequencies of material-substance and process ideas across sessions. In other words, this analysis attempts to highlight the patterns in terms of where material-substance and process ideas are most likely to show up. As Table 2 shows, process ideas were significantly underrepresented in the interview sessions, whereas they were significantly overrepresented in the animation sessions. That is, process ideas appear less likely in the initial oral language settings than expected, and more frequently in animation session than expected. With Trish, the animation provided her with an opportunity to explore the ways in which particles interacted in the system, thus leading her to externalize a number of process ideas during the session.

In addition to utterances, the students’ productions were also coded for differences between material-substance and process aspects of air. Productions were coded using a similar set of codes as the utterances, with some additional codes used to categorize elements of the productions. Table 3 shows the frequencies of material-substance and process codes present in
Table 2. Utterances across sessions, grouped by conceptual aspects of air (i.e., material substance and process).

<table>
<thead>
<tr>
<th></th>
<th>Interview</th>
<th>Drawing</th>
<th>Animation</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material - Substance</td>
<td>57</td>
<td>84</td>
<td>73</td>
<td>78</td>
</tr>
<tr>
<td>% of total material substance utterances</td>
<td>19.52</td>
<td>28.77</td>
<td>25.00</td>
<td>26.71</td>
</tr>
<tr>
<td>Chi Square</td>
<td>2.401</td>
<td>1.135</td>
<td>0</td>
<td>0.235</td>
</tr>
<tr>
<td>Process</td>
<td>27</td>
<td>50</td>
<td>83</td>
<td>60</td>
</tr>
<tr>
<td>% of total process utterances</td>
<td>12.27</td>
<td>22.73</td>
<td>37.73</td>
<td>27.27</td>
</tr>
<tr>
<td>Chi Square</td>
<td>12.959**</td>
<td>0.413</td>
<td>12.959**</td>
<td>0.413</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, *** p < 0.001

the productions organized by type of production (oral language was not included in this analysis, as the analyses displayed in Tables 1 and 2 focused on utterances). While Tables 1 and 2 display the frequency of utterances, Table 3 shows the total number of material-substance and process ideas represented by all students in each category of production. The null hypothesis was that material-substance and process ideas would be equally probable in each of the productions. The data suggest that material-substance ideas are more frequently represented in drawings than expected, and less frequently present in physical constructions than expected. Similarly, while not significant, process ideas are represented in animations more than was expected. As Table 3 shows, the frequency of material-substance ideas and process ideas represented in the physical constructions was quite similar. This trend is of interest, as the act of representing an unseen (such as air) in a physical, visible medium creates the problem of selecting a material to stand for the unseen air molecules. Perhaps efforts to represent process ideas are inextricably linked with efforts to represent the material substances involved. This makes the physical representation task
an interesting case for analyzing representational solutions provided by students. Overall, the results suggest a relationship between conceptual aspects of air and systems of representation. These results are further expanded upon in discussion section.

Table 3. Productions across sessions, grouped by conceptual aspects of air (i.e., material substance and process).

<table>
<thead>
<tr>
<th></th>
<th>Drawing</th>
<th>Animation</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material – Substance</strong></td>
<td>40</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>% of total material</td>
<td>54.79</td>
<td>27.40</td>
<td>17.81</td>
</tr>
<tr>
<td>Chi Square</td>
<td>27.749***</td>
<td>2.093</td>
<td>14.41***</td>
</tr>
<tr>
<td><strong>Process</strong></td>
<td>10</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>% of total process</td>
<td>28.57</td>
<td>40.00</td>
<td>31.43</td>
</tr>
<tr>
<td>Chi Square</td>
<td>1.3429</td>
<td>2.696</td>
<td>0.210</td>
</tr>
</tbody>
</table>

* p < 0.05, ** p < 0.01, *** p < 0.001

7.0 Discussion

For the small group of students participating in this study, the process of constructing representations across multiple systems helped them to explore different conceptual aspects of air and, thus, develop a more sophisticated understanding of air and the particle model of matter. The context for the investigations was specifically chosen such that students would observe changes over time. With the linked syringes, students were able to explore multiple processes including compression of a gas and force transfer through a gas. Additionally, the adoption of a particle model of matter provided the students with resources for contemplating the processes
they observed at a potentially deeper level than the more continuous models many of them initially held. Thus, the exploration itself (i.e., the linked syringes) must be considered in this study, as inherent in this device were opportunities for students to explore both material substance and process aspects of air.

The data suggest a relationship between specific systems of representation and certain conceptual aspects of air, for the participants in this study. The students demonstrated a tendency to focus their utterances and productions on material substance aspects of air in the interview and drawing tasks. Drawing is a relatively static system of representation, whereby showing motion and processes can be considered more challenging than in other, more dynamic systems of representation. Conversely, drawing offers opportunities for careful analysis of moments in time, including the material substance qualities of air at a given moment. Students’ attempts to represent their understanding of air in oral language and in drawing resulted in a tendency to focus on what air is. With Trish, for example, we saw her struggle to articulate an explanation of air during the interview and in her first drawing. Trish successfully described what she observed, and her drawing listed some key aspects of the linked syringe system (e.g., the requirement of a “contained space”); however, her representations (both oral and in drawing) did not offer detailed explanations of why the system behaved as it did. The same was true for Fernando, who focused primarily on the idea of air “flows” in his initial verbalizations and drawings of the linked syringes – representations perhaps also linked to Fernando having a continuous model for air.

The introduction of a particle model (by the interviewer) initiated a change in both Trish and Fernando’s ways of representing the situation. However, these new particle utterances and the inclusion of “dots” in their drawings remained focused on making sense of air as a substance
(i.e., a collection of particles). Fernando incorporated particle ideas in the drawing session (both orally and in his production), but he neglected to include particle ideas in his animation, which was primarily focused on the process of how air behaved in the syringes. For Fernando, the idea of particles remained localized in his thinking about material-substance ideas, at least initially. Alternatively, as Trish contended with the problem of representing air, the development of particle ideas lead her to begin considering the processes demonstrated by the linked syringes. Trish included particle ideas in her animation, using particle representations to make sense of, for example, why air could be compressed in the syringe device. For both students, particles were useful but in thinking about different aspects of air in sessions focusing on different representational forms. The impact of the introduced “air as dots” representation shows how students having opportunities to interact with representations different from their own may assist them in making sense of situations such as the linked syringes. Ultimately, this can also be taken as evidence of a relationship between types of representations and conceptual aspects of air.

The quantitative analysis confirms the finding that there may, in fact, be a relationship between the systems of representation and the conceptual aspects of air externalized by the participants. Table 1 demonstrates the frequency distributions wherein material-substance ideas were much more prevalent than expected in the interview and drawing sessions. Table 2 shows that across all systems, process ideas are more likely to be represented during the animation session than expected. This trend is enlightened by further analysis of the affordances of the animation environment. With stop-motion animations, students engage in a process of showing change over time. A movie has an inherent temporal dependency whereby each frame is reliant on the previous frame, as well as the upcoming frame. When a student is creating a single frame (e.g., by moving dots of paper along a syringe drawing, such as the case with Trish), he or she
must be mindful of the previous frame, as well as the next frame. In other words, generating one instance of the movie involves knowing where you came from and where you are going. This implicit temporal dimension of animation can be considered as an affordance that promotes exploration of change over time (i.e., processes). Perhaps students tend to focus on process ideas while engaged in generating an animation because the system itself is better suited to representing processes. The data from the productions is less clear, but still suggests an increase in the number of process ideas represented in the animations as compared with drawings or physical constructions. For Trish, the animation was a way to demonstrate her understanding of compression as well as a representation for force transfer. As the literature suggests, both of these concepts are notoriously challenging for students, yet Trish demonstrated capacity for grappling with process ideas. Fernando may not have used particle representations, however, his animation still concerned issues of compression and resistance felt in the handles of the syringes, which are both considered to be process concepts. While I take care not to conjecture too strongly about the production data, it warrants future investigation into aspects of animation that may make it a powerful medium for exploring change over time.

The physical construction task may be the most abstract system utilized in the study, as building a conceptual model is a formidable challenge. Those with mastery of the conceptual domain may find difficulty in selecting appropriate materials to represent the concept; however, this challenge may be beneficial for students trying to make sense of air. Constructing a physical representation of air requires selecting an element to “stand for” the substance, while also representing some aspect of the context and how it changes over time. When constructing the stand-for relationship, the student is faced with having to confront any assumptions or presuppositions he or she holds about the substance. With Trish, she continually remarked how
the ball bearings she selected to stand-for air were *not* like air molecules. Making explicit the differences between the representation and the referent may have helped Trish develop a richer understanding of air as particles; engaging in a process of externalizing an idea and re-linking those external representations to her model for air likely led to changes in Trish’s understanding. In terms of systems of representation, perhaps physical constructions yield a more equivalent distribution of process and material-substance utterances because efforts to represent the process are inextricably linked with choosing a suitable representation for the substance. Trish wanted to show her understanding of how the air molecules moved through the system, which for her was dependent on describing how the metal ball bearings were *not* acting as she believed air molecules would. This particular affordance of the physical construction form of representation could help students construct integrated understandings of processes and material substances, which I consider to be a more complete, advanced understanding of a topic such as air and the particle model.

The particular nuances of how certain conceptual aspects are more likely represented in which system require further investigation, particularly with a larger sample. However, one summative finding appears relatively clear: students tend to represent different ideas in different systems of representation and, thus, should be given opportunities to do so in science classes. Asking students to externalize their understanding in multiple ways not only allows them to explore aspects of their own thinking, but also provides the researcher or teacher with a multi-dimensional view of what the student believes and how they represent their ideas. Students engaged with a single system of representation may lack the opportunities to challenge their thinking and may be deprived of the chance to refine their models for how the world works.
Therefore, I promote the use of multiple forms of representation in the exploration of science concepts.

In addition to the relationships between conceptual aspects of air and systems of representation, there are additional issues related to the literature on students and science learning that deserve attention. First, as others have suggested (diSessa et al., 1991; Enyedy, 2005), students engaged in a process of progressive symbolization develop increasingly sophisticated understandings of science and mathematics concepts. Externalizing and re-representing ideas in a cyclical nature, as the students in this study were asked to do, aides the development of conceptual understanding as well as the development of the abilities to externalize ideas (Kaput, 1991). As with Trish, the incorporation of particle ideas from the time they were introduced through the remaining sessions shows how that particular idea or model proved useful for her. With Fernando, his adoption of the particle model was not as immediate, but still proved useful as he tackled more complicated process ideas related to the syringes. Concurrently, both students’ representations of particles and how they interact gained complexity in each re-representation (or representational redescription as Karmiloff-Smith (1990) might suggest). I offer this as evidence of the power of iterative representation in science learning. I also recognize that Karmiloff-Smith’s (1990) and Enyedy’s (2005) constructs are rooted in how students develop an understanding of conventional representations such as mathematical notation and written language. Even though representations of air were not based on elements from conventional systems (e.g., written number), students in this study underwent a process of creating representations that became conceptual objects in much the same way as the literature describes conventional elements as objectified concepts. With Trish, a discussion of how a ball bearing is not like an air molecule presumes that the ball bearing has effectively become part of
the concept of an air molecule, as its limitations could not be considered until its status as “representation” was accepted. While not conventional, representations as objects allow the students to evaluate their externalizations en route to generating a more refined and sophisticated re-representation. I believe the interplay between the process of generating representations and the evaluation of these products as conceptual objects suggests that there is no strict dichotomy either developmentally or conceptually between process and object. In other words, the process of representing is also a process of objectifying – occurring simultaneously in some cases, such as with Trish and the discussions of how a ball bearing is not an air molecule.

Similarly, these data suggest that the distinction between process and material-substance aspects of science concepts (suggested by Chi, 1992) may need reconsidering. While Chi (1992) articulates the differences between process aspects and material-substance aspects of a concept such as air, from a theoretical standpoint, I propose that the process of representing those aspects across multiple systems allows students to concurrently develop understandings of how process and material-substance ideas are related. The context of externalizing understanding through the production of multiple representations allows students to explore how material-substance and process ideas can be integrated, as opposed to in conflict with each other. It can be argued that this integration of process and material-substance ideas is necessarily for a full and complex understanding of air. Much of Chi’s work (see Chi 1992; Slotta, Chi, & Joram, 1995) illustrates the difficulties students have with switching between material-substance and process ideas; however, perhaps the lens of multiple representations may help the students make these transitions; maybe the point and focus should be on integration and not transition. Again, more work is needed to provide sufficient evidence of this process/material substance debate, but I feel this issue deserves greater attention. Fernando constructed the concept of a “barrier” or “wall”
that was causing resistance in the syringe system as a result of air being compressed. In his attempts to make sense of this process, he was lead to further engage with the problem of representing air as a substance. Similarly, in the case of Trish, the introduction of a particle model of air provided her with a representation of the material substance that aided her investigations of processes. In turn, her efforts to conceptualize the processes inherent in the linked-syringe case forced her to reassess her understandings of material substance. Therefore, this approach to unpacking a concept such as air and the particle nature of matter through representational re-descriptions across multiple systems may be powerful in inducing shifts in foci and changes in conceptual understanding.

8.0 Future work

The data presented here suggest a deep, complex relationship between external representations and various aspects of science concepts, such as air. However, continued investigation into this relationship could increase its impact on the field of research and intervention in science education. The process versus material substance distinction used in the quantitative analysis revealed compelling trends across each system of representation. However, as the excerpts from Trish and Fernando’s interviews illustrate, both the utterances and productions possess rich and complicated conceptions of air and the particle nature of matter that could be probed in greater detail. Improved coding schemes and methods for categorizing not only the ideas but also the ways in which these ideas are represented in each of the sessions is needed. An increased sample size as well as the potential introduction of additional content topics (such as heat or light) would strengthen these findings as well.
An important implication of this study for education could lie in the introduction of a particle model to middle school-aged students. As Papageorgiou and Johnson (2005) suggest, a particle model of matter is useful in helping students contemplate issues of material substance. I feel these data also suggest that students of this age are capable of thinking about air as particles and are able to use this particle representation in the exploration of process ideas. For Trish, the introduction of air as dots on paper led her to consider a particle model, which proved useful in her contemplation of more advanced ideas such as compression and force transfer. Furthermore, the opportunity to represent a concept in multiple ways helped both Trish and Fernando transition between different conceptual aspects of air as well as to undergo changes in their conceptual understanding. Therefore, the introduction of a particle model coupled with the process of progressive symbolization across multiple systems of representation proved a successful strategy and could be thought of as a potential classroom intervention.
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Appendix A: Materials provided in the physical construction interview session. All materials were presented to each student so that they may manipulate and explore them in the process of constructing their physical representations.

- 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 and lengths
- Clear plastic flexible tubing (~3-4 mm inner diameter)
- Popsicle sticks
- Masking Tape
- Duct Tape
- Adhesives (glue, glue gun, quick-drying epoxy)
- Binder Clips
- Clothes pins
- Velcro
- Springs (assorted)
- Zip ties
- Straws
- Cork stoppers
- Paperclips
- Plastic spoons, knives, forks
- String
- Marbles
- Cotton Balls
- Balloons
- Rubber bands (thick and thin)
- Steel ball bearings, small (~1 mm diameter) and larger (~3-4 mm in diameter)
- Paper cups
- Balloon Pump
- Bicycle Pump
Appendix B: A list of codes is included, grouped according to whether the code pertained to material-substance ideas or process ideas about air and particles.

**Material Substance Codes**

Air takes up space
Air has mass/volume
Air is made of gases
Air is made of particles
Air particles float
No empty space
Air is invisible
Air molecules are in intrinsic motion
Utterances pertaining to bulk props of air
Continuous ideas about air – concentrated distributions
Continuous ideas about air – mixed distributions
Continuous ideas about air – expanded/even distributions
Spontaneous particle representation
Prompted particle representation
Particle ideas about air – concentrated distributions
Particle ideas about air – mixed distributions
Particle ideas about air – expanded/even distributions
Comparisons of gases, liquids, and/or solids

**Process Codes**

Ideas pertaining to compression
Air pushes against things
Air transmits forces
Representation (oral or other) of a force transfer mechanism
Compression in the syringes leads to a force felt on the syringe plungers
Compression leads to no space between particles, completely packed
Idea or representation of compression using some comparative
Different particle spacing in different contexts