ABSTRACT

Title of Dissertation: **ANALOGIES AS CATEGORIZATION PHENOMENA: STUDIES FROM SCIENTIFIC DISCOURSE**

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Studies on the role of analogies in science classrooms have tended to focus on analogies that come from the teacher or curriculum, and not the analogies that students generate. Such studies are derivative of an educational system that values content knowledge over scientific creativity, and derivative of a model of teaching in which the teacher's role is to convey content knowledge. This dissertation begins with the contention that science classrooms should encourage scientific thinking and one role of the teacher is to model that behavior and identify and encourage it in her students. One element of scientific thinking is analogy. This dissertation focuses on student-generated analogies in science, and offers a model for understanding these. I provide evidence that generated analogies are assertions of categorization, and the base of an analogy is the constructed prototype of an ad hoc category. Drawing from research on categorization, I argue that generated analogies are based in schemas and cognitive models. This model allows for a clear distinction between analogy and literal similarity; prior to this research analogy has been considered to exist on a

spectrum of similarity, differing from literal similarity to the degree that structural relations hold but features do not. I argue for a definition in which generated analogies are an assertion of an unexpected categorization: that is, they are asserted as contradictions to an expected schema.

ANALOGIES AS CATEGORIZATION PHENOMENA: STUDIES FROM SCIENTIFIC DISCOURSE

By

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Dedication

For women in physics.

…As I say, I can speak only for myself,
but as soon as I got here the rules became different.
They didn't apply to me any more, or to anyone else except a distant runt,
almost invisible in its litter. So how was
I to know who to stand up to, when to turn abrasive, when all things
    nestled,
equidistant, all hearts were charming, and it was good to be natural and
    sincere?…

School was over,
not just for that day but forever and for seasons to come.
The reason was that the truth was just average
on the iniquity scale, and nobody wanted to get involved…

You see we all thought the ride would be lovely
and worth the trip, which it was, but now we cannot go anywhere
having already been everywhere. No, do you
understand how realistic it all is?…

And so we faced the new day
like a pilgrim who sees the end of his journey
deferred forever.
Who could predict where we would be led, to what
extremes of aloneness? Yet the horizon is civil.

-Ashbery, *Girls on the Run*

Acknowledgements

The idea behind this thesis is that the theories we develop with our *science* are analogies to the stories that we tell with our *lives*. And so this dissertation holds a mirror to my life and reflects its stories – the stories that have brought me here and brought about this work. And those stories have as much to do with community and friendship as they do physics and education. I would like to acknowledge all of my friends, in particular Dorothy, Kathryn, Noam and Sam, for conversation about the things that matter, and my Seattle roommates – especially Amber, Laura, Manu and Sam – for creating a true home. I would like to thank Jerry Seidler, in whose lab I discovered that I did not want to do experimental physics and I was given the freedom and support to decide that. I thank Stamatis Vokos, the deus ex machina of my story, and Joe Redish, both of whom took risks for me and I am grateful for and buoyed by their trust. Graduate students Matty, Paul and Rosemary provided hours of critique and conversation in helping me hone the details of this thesis and kept me smiling through the massive frustrations. And friends outside of graduate school, Wendy and Anne in particular, reminded me of life beyond academia, while the Elliott family gave me hope that academia could be everything I wanted it to be. Were it not for my education at the Governor's School of North Carolina, both as a student and a teacher, I would never have seen myself as someone with a story to tell or a theory to share. The work that happens there is incredible and profound. Thank you to Mrs. Liz Woolard, my brilliant high school physics teacher. And to Janet Coffey who is going to be an amazing professor and advisor and was so encouraging – especially in the final stretch. The teachers from SIPS

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For Richard, you know my whole story – told over lunches in the physics courtyard, driving across the country, along the West Coast Trail, in Chamonix, Bear Lake, Mazama, and, too many times, over the phone late at night. I am so lucky. You're for me.

And finally, for my family: mom, dad, Sara and Ben. Thank you. *Your love is tremendous*.

Table of Contents

Chapter 1: Introduction and Major Themes

Introduction

> Metaphor is the currency of knowledge. I have spent my life learning incredible amounts of disparate, disconnected, obscure, useless pieces of knowledge, and they have turned out to be, almost all of them, extremely useful. Why? Because there is no such thing as disconnected facts. There is only complex structure. And both to explain complex structure to others and, perhaps more important – this is forgotten, usually – to understand them oneself, one needs better metaphors. If I was able to understand this, it was because my chaotic accrual of information simply gave me better metaphors than anyone else…
>
> Translate a concept from its field for use to where it is unknown, and it is always fresh and powerful. In buying outside, you are doing intellectual arbitrage. The rate limiting step in this is your willingness to continuously translate, to force strange languages to be yours, to live in between, to be everywhere and nowhere.
>
> -Burr, 2002

Many scientific theories evolve from analogy – noticing links others have missed or relating a fact that others have not noticed. Luca Turin (Burr, 2002) related the mechanism for smell to electron tunneling spectroscopy. The arguments and evidence for his model came not from chemistry or biology, but perfumery and jet fuel technology. Einstein was a patent clerk in an era when trains were fast becoming a primary means of transportation. Many patents of this time concerned synchronizing clocks, and Galison has proposed that considering this problem in the context of what Einstein knew from physics led him to his theory of relativity (Galison, 2003). Faraday's research notes express deep analogical reasoning: thinking of electro-magnetism in terms of lines in space (the "field concept") (Nersessian, 1985). Maxwell related magnetism to vortices and "idle wheels" (Nersessian, 2002). Kosterlitz and Thouless (1973) related 2-

dimensional phase transitions to topology. The scientific literature is overrun with breakthroughs that developed from analogical reasoning – relating seemingly unrelated topics that, once related, establish a new research paradigm.

The use of analogies in science is not restricted to insights from creative scientists, but is part of the regular patter of students and instructors when discussing scientific ideas. In the following transcript, undergraduates in a conceptual physics course have been exploring static electricity in conductors and in insulators. The students have worked in small groups, discussing the differences between what it’s like for a charge in metal versus Styrofoam, and are now reporting and discussing their conclusions with the instructor (transcript 1, lines 41 – 107):

Christie: Like they were just saying in metal it’s [the charge is] always moving. So if it’s always moving it has more room to move and that would mean to say that the molecules are, like, less tightly packed together or less dense. And we were thinking of Styrofoam as more dense then – I’m just trying to figure out first if that’s right and how it relates.

Lea: Alright I, going on that idea. I don’t agree with you saying that the Styrofoam is more dense I think it's less dense. And so that’s why the charges get caught up in it. 'Cause it's like – like cotton. And the, the pan is more dense and so they’re able to slide across it like they can ice skate across it easier. So that’s why they move around more 'cause it’s more dense so they can slide across it more and the Styrofoam is less dense and so they get stuck in it. Like they can’t move as much.

Instructor: … I’m thinking of like, pouring water into a sponge versus pouring water onto a hard surface. Like this sponge is actually less dense and there’s room for it to absorb the water and the you know if you pour it onto something hard there’s no room for it to absorb.

Anna: You’re saying that the charge is, like, on top of the metal? Like on the outside?

Lea: Yeah. Hold on-I mean-I don’t-

Anna: I think it’s like made up of it-like, they’re electrons.

Lea: Like, I don’t know. But it’s definitely a lot smoother, like, and they’re they’re denser and so they can move around more freely.

Paul: I just want to- I know there are people here- I just want to clarify Lea and Anna your question, your question was 'Is charge moving on the surface as opposed to moving inside.' Right? And so this would be like are the fish swimming in the middle of the fishbowl or are they sort of somehow stuck to the edge of the fishbowl…

Lydia: Alright, well I was going to say it makes sense to me if the pie plate is more dense, then it would be easier for them to move within it. But I do think that it's inside of the metal not outside. Because it's harder- I mean, if there's more space to travel like in the foam, you can't get from one place to another easily but it's all real close together so it can sort of hop along inside.

Paul: Oh so it's like stepping stones?

Lydia: Kind of.

Paul: Like in the Styrofoam it's really far [Lydia: Like yeah.] to the next stepping stone and so I can't get there I'm stuck here. [Lydia: Right] But in the metal the stones are really close together and so then I can kind of just walk across.

Notice the analogies drawn in the brief transcript above: the motion of electrons in metal is like ice-skating, the metal is like a countertop or closely spaced stepping-stones. Styrofoam is like a sponge or cotton. What cognitive work does this do for the students? Why are these analogies chosen? How do they influence the resulting theories the students develop? What do these analogies reveal about the way the students conceptualize the world?

There is no shortage of research to turn to in addressing these questions and seeking to understand analogies in science. Research from education, cognitive science, linguistics, anthropology, and the history and philosophy of science all have something to say about the analogies that the scientists and students are employing. This dissertation draws from all of these fields, together with analogies generated by students in science classrooms and study groups, in constructing a model for generated analogies in science and explores the implications of this model on science instruction.

A brief history of analogy research

> What cognitive capabilities underlie our fundamental human achievements? Although a complete answer remains elusive, one basic component is a special kind of symbolic ability – the ability to pick out patterns, to identify recurrences of these patterns despite variation in the elements that compose them, to form concepts that abstract and reify these patterns, and to express these concepts in language. Analogy, in its most general sense, is this ability to think about relational patterns.
>
> -Holyoak, Gentner and Kokinov, 2001

Analogies, long recognized as being far more than figurative, expressive forms of speech, have frequently been used as tools for teaching students about science (Clement, 1993, Gick and Holyoak, 1983) and the benefits of this has been explored extensively. The story that this research tells suggests that the base of the analogy – the sponge, say, or the stepping-stones in the transcript above – is the cognitive foundation for the analogy. It is from this base that students extrapolate a structure and map onto a target.

But there are several things problematic with this story when applying it to student-generated analogies in classrooms. First, the story contradicts other findings from education that inform us that we do not have single, unitary representations of concepts in mind that can be mapped onto others. Second, it is a model built from studies regarding how students interpret and understand analogies that they are given – or even how we, as teachers, come to understand their analogies – but not the things students are doing when they assert analogies. If generating, critiquing and working with analogies are part of the practice of science we want students to learn, we need to better understand moments like the one above, in which students generate analogies and the analogies introduced by the instructor are responsive to student ideas rather than content goals. Because of the focus on the interpretation of analogies less well known, researched and understood are the ways in which analogies are constructed by students seeking to explain the world in a scientific way (May, Hammer and Roy, 2004).

Major themes

The story I want to tell, using analogies generated in student scientific discourse and in science as it is practiced, is one of analogies as assertions of categorization – in particular, a categorization that is unexpected. Categories, as I will explain in the following chapter, stem from our cognitive models of the world, built from schemas. Lea's analogy to ice-skating (presented at the beginning of this chapter) is, first, an acknowledgement that density typically makes motion difficult. Her analogy is asserting that another manner of categorization exists for dense media: there are those that, by virtue of their density, make motion easier. The interpretation of analogies as assertions of categorization echoes Eva Feder Kittay's (1997) comments with regard to metaphor – made in the field of linguistics, outside of physics and education.

> If metaphors do not report an antecedent similarity, but instead create the similarity, they do so by dislodging some items from familiar classifications and regrouping them with items that normally belong to different, even disjoint categories. So dislodging and regrouping items or subclassifications not only creates a new category, but also disrupts normal classifications.

This thesis will outline the reasoning behind the "normal classifications" that we have, based on Lakoff's research in idealized cognitive models and diSessa's theory of phenomenological primitives. Furthermore, the bases of analogies are explained in this context as arising from the categories that are constructed from cognitive models and are the ad hoc, constructed prototypes of these categories.

The ontology of mind implicit in this theory is compared with other theories of analogy, in particular structure-mapping (Gentner, 1983). I argue for a manifold, small scale, “knowledge-in-pieces” ontology of mind and support this argument with data from other findings in cognitive science, linguistics and education.

Finally, this thesis has strong implications for instruction, education research and cognitive science, starting from the premise that generating analogies should be an important part of the science classroom – *not* as a tool for acquiring content knowledge but as a goal of a science education because it is, in part, what science *is*. Second, the focus on interpreting analogies and lack of attention to generated analogies is challenged: such a focus misses the cognitive flexibility and utility of most analogies, as analogies are surely generated more often and with greater effect than they are interpreted. Third, the ideas underlying “transfer” and “misconceptions”-based curricula are called into question. Finally, I caution research – in particular education research – against “in vitro” studies that are not balanced by “in vivo” studies of cognition in the wild. Applying findings generated in laboratories that limit cognitive variability and lack the context of a classroom to educational and other “real world” scenarios can result in a detrimental shift of focus from students’ abilities and the variability of student reasoning to a focus on a unitary conception of students’ reasoning and abilities.

Chapter overview

Chapter Two: Review of the literature

In the following chapter, I will outline the existing research on analogies and categorization. My emphasis is on the characteristics of generated analogies and categorization, and not by what mechanism the mind creates schemas and their associated categories. I present research from cognitive science and linguistics on analogies and metaphors and the role that analogies have played in science education. Then I outline the research on categorization and the interplay between categories and idealized cognitive models. Research from physics education on phenomenological primitives is then related to the idealized cognitive model. Finally, past research relating analogies to categorization is reviewed.

Chapter Three: Methodological Considerations

This chapter is dedicated to outlining the history of research in analogical reasoning and situating my methodology within this history. In particular I focus on the methodology of past research and the kind of information that this methodology affords. The limitations of laboratory-based studies are addressed along with the philosophy of mind and of causality that are inherent to these studies. I then overview more recent studies of analogy and the more qualitative methodologies of these along with the advantages and limitations of these approaches. I then explain the approach that I take, the philosophy behind this approach and the information that can and cannot be gleaned from this research.

Chapter Four: The phenomenological evidence

A distinction has been made in the literature between behavior – the observable part of cognition – and cognitive structure – the underlying ontology of mind responsible for that behavior. Chapters four and five address these two sides of cognition, chapter four focusing on cognitive behavior and five on the underlying cognitive structure. In this chapter I first review past research on categorization, focusing on the observable structure of categories, and contrast that with existing research on analogies. I then present transcripts from students in science classrooms, study groups, research groups and faculty and present an argument for the interpretation of analogies in a categorization framework, basing this interpretation on the behavior. These claims will be contrasted with other models of analogy, in particular structure-mapping and transfer. The analogies discussed here will be explored again in the following chapter for their implications on cognitive structure.

Chapter Five: Cognitive structure and analogies

Having presented phenomenological evidence for analogies as categorization, in this chapter I focus on the underlying cognitive structure that can account for that behavior and is consistent with a categorization interpretation of student-generated analogies. I begin this chapter with a review of the different approaches that have been taken in the past to cognitive structure in both education and cognitive science and present arguments in favor of a manifold ontology of mind. Analogies presented in the previous chapter are then revisited for their consistency with this manifold ontology.

Chapter Six: Analogies in the history of science

Though this thesis does not focus on the history of science and the evolution of scientific theories, several findings from the history of science can be brought to bear in defense of my claims. In this chapter, I briefly outline research in the history of science and cite several theories and ideas that have evolved via analogy. These ideas demonstrate that important concepts in science arose from schemas provided by changes in our political systems and our technology. I outline these theories and their development and show how it is consistent with a categorization model of analogy. Finally, I show how a study in the history and philosophy of science has changed the definition of a concept and how this new definition, which is rooted in the idea of conceptual change via physical analogy, is consistent with the categorization framework of generated analogies.

Chapter Seven: Implications for instruction.

There are three main points that I would like to make with regard to science instruction with this thesis. The first point reflects my motivation behind studying student-generated analogies: the use of analogies and analogical reasoning is, in large part, what it means to do science. Content knowledge of the science disciplines is important, but even more so is the ability to think scientifically: to be able to understand that content knowledge as it relates to theories and experiences that you have, to be able to create your own models using analogies to concepts that you understand and find familiar, to understand the implications of these models and negotiate these analogies: in essence, to create your own knowledge from your own experience in a scientific manner. If we accept this first claim, that science instruction should emphasize how to create and negotiate analogies, our conception of what analogies are matters and will influence the way in which a teacher identifies and responds to analogical reasoning in the classroom. The second point, then, is that analogies are not indicative of a fixed representation of a particular concept. The mind is far more fluid and complex than that. Understanding analogies as assertions of categorization requires that instruction be sensitive to this variability, for categories are inherently variable. And third, by understanding analogies as assertions of categorization, questions of transfer – the holy grail of education – become not questions of near and far transfer, but of prototypical and aprototypical analogies. How this translates into practice will be explored in further detail in this chapter.

Chapter Eight: Directions for future research and conclusion.

While I make claims about *what* analogies assert, I have not come to any conclusions about *how* this happens. What habits of mind and what structure of education and environment can encourage this kind of creative re-categorization of concepts? Nor do I explore theories that are not built from analogy or have no obvious analog or the extremely significant role that community and dialog plays in both constructing and negotiating an analogy. In the final chapter, I summarize my conclusions and introduce these questions and suggest directions for future research on these topics.

Appendix A-J: Transcripts

Included in the appendix are full transcripts from conversations in which the analogies presented in the dissertation are taken. These transcripts are referenced in the chapters, so the reader may find the entirety of the transcript that I had available. In some cases, these transcripts span entire class-periods of discussion; in other cases, only a short piece of that conversation exists.

Appendix K: Young Children's Analogies and Transcripts

Chapters 4 and 5 presented several analogies from student conversations in science, and chapter 6 details analogies by professionals in science and related fields. In the appendix I address analogies that were not included in previous chapters, particularly those asserted by younger students. These students are able to generate analogies (for example, magnets are like clay) but lack explicit awareness of that analogy. These students are confused by the mapping to the target, or confuse the assertion with literal class inclusion (so that magnets are not *like* clay but *are* clay). This confusion is consistent with findings from Karmiloff-Smith (1992) on representational redescription and is predicted by Glucksberg's et al. (1997) dual reference theory. Structure-mapping and other theories that limit analogies to pairwise analyses of the target and base would not predict and cannot account for the confusion young students show between statements of class-inclusion and statements of superordinate-class-inclusion.   This chapter presents theories and findings of representational redescription, dual reference, semantic fields and polysemy and argues that, in light of those findings, the mistakes and confusions that young students display with analogies are consistent with a categorization interpretation of analogy.

Chapter 2: Review of the Literature

Introduction and Overview

In the latter half of the 20th century research in two fields, categorization and analogy, has challenged long held classical views of these topics. Up until the nineteenth century, discussions on analogy, and in particular metaphor, were insistent on one theme: analogies are decorations of speech; they do not contribute to the cognitive meaning of the discourse, but instead lend it color, vividness, emotional impact, or accessibility. Thus it was characteristic of the Enlightenment philosophers and their predecessors, such as Hobbes and Locke, to insist that though philosophers may sometimes have good reason to communicate their thoughts with metaphors, they should do their thinking entirely without metaphors. Only by using nothing but unambiguous, literal language could knowledge be gained and communicated properly (Hobbes, 1651):

> To conclude, the light of humane minds is perspicuous words, but by exact definitions first snuffed, and purged from ambiguity; reason is the pace; increase of science, the way; and the benefit of mankind, the end. And, on the contrary, metaphors, and senseless and ambiguous words are like ignes fatui; and reasoning upon them is wandering amongst innumerable absurdities; and their end, contention and sedition, or contempt.

Similarly, John Locke, in the Essay Concerning Human Understanding, criticized imprecise and ambiguous “civil” language and proposed a proper and well-defined philosophical language that “may serve to convey the precise notions of things, and to express in general propositions certain and undoubted truths, which the mind may rest upon and be satisfied with in its search after true knowledge” (Locke, 1686).

What characterizes almost all theories of metaphor from the time of the

Romantics up through the twentieth century is the rejection of this theme. Metaphors, it has been argued, are not cognitively dispensable decorations. They contribute to the cognitive meaning of our discourse and they are indispensable, not only to philosophical discourse, but to ordinary, and even scientific discourse. Nietzsche went so far as to argue that all speech is metaphorical and truth is “a mobile army of metaphors” (Nietzsche, 1873). Lakoff and Johnson’s seminal work, *Metaphors We Live By* (1980), begins with the statement of traditional interpretations of metaphor and summarily reject this interpretation:

> Metaphor is for most people a device of the poetic imagination and the rhetorical flourish – a matter of extraordinary rather than ordinary language… We have found, on the contrary, that metaphor is pervasive in everyday life, not just in language but in thought and action. Our ordinary conceptual system, in terms of which we both think and act, is fundamentally metaphorical. (p3)

This shift in understanding of the importance of analogies – from ornamental to fundamental – has resulted in the emergence of research in the structure and comprehension of analogy. The results of this research will be addressed later in this chapter.

Categorization, too, has experienced a dramatic reinterpretation in the 20th century. As Lakoff summarizes in *Women, Fire and Dangerous Things: What Categories Reveal about the Mind* (p 6):

> From the time of Aristotle to the later work of Wittgenstein, categories were thought [to] be well understood and unproblematic. They were assumed to be abstract containers, with things either inside or outside the category. Things were assumed to be in the same category if and only if they had certain properties in common. And the properties they had in common were taken as defining the category.
>
> This classical theory was not the result of empirical study. It was not even a subject of major debate. It was a philosophical position arrived at on the basis of

> a priori speculation. Over the centuries it simply became part of the background assumptions taken for granted in most scholarly disciplines. In fact, until very recently, the classical theory of categories was not even thought of as a *theory.*

Current theories on categorization have shifted from this Aristotelian view towards what has become known as the “prototype” view, the importance of which was first established by Rosch (1973). This shift in our understanding of categorization can be traced to the Whorfian hypothesis, which claims that language is not merely a medium for the expression of our thoughts but that “linguistic patterns themselves determine what the individual perceives in this world and how he thinks about it. Since these patterns vary widely, the modes of thinking and perceiving in groups utilizing different linguistic systems will result in basically different world views” (Fearing, 1954). Rosch’s tests of the Whorfian hypothesis led her to study the nature of color categories among speakers of languages without a blue-green color distinction. In these studies, she identified structure within categories, with some members of a category being seen as more or less prototypical than others. This recognition, with its associated research paradigm, launched a field of study into categorization that has come to be characterized as the “prototype” view. More recent developments in this field have extended the types of categories studied from “common, or stable, categories to *ad hoc* categories” (Shen, 1992) – from Rosch’s study of color categories to Barsalou’s study of “things to take from your house during a fire.” The results of this research and its implications on cognitive structure will be discussed later in this chapter.

It has not gone unnoticed that these two research programs, analogy and categorization, are both studies of similarity and each may have insights that might inform the other, but as late as 1992 it was remarked: “Despite the obvious affinity of these two fields of research, the link between them has received little attention in cognitive psychology or in other disciplines" (Shen, 1992). Shen and others (most notably Glucksberg and Keysar), have, during the 1990's, dedicated study to linking these two research enterprises. However, the emphasis of this research has been on metaphors and their interpretation, developing "a coherent and unified framework by assuming that metaphor interpretation is, in fact, a process of ad hoc category formation" (Shen 1992), and "a basis for a theory of metaphor comprehension, and also clarifies why people use metaphors instead of similes" (Glucksberg and Keysar, 1990). It is the aim of this thesis, in the context of scientific discourse, to extend the link between metaphor and categorization to include analogical statements and to argue that the statement of an analogy – not merely its comprehension – is an assertion of categorization. Below I will outline the existing research on analogies and categorization, along with the research that attempts to link these two fields of study, in more depth.

Analogies

Analogies in philosophy and the philosophy of science

The modern views of analogy can be traced to the influences of philosophers Max Black (1962) and Mary Hesse (1966). Black's work built on that of Ivon Richards' (1936) work in the field of rhetoric, who proposed a set of useful terms for talking about metaphors (the "topic" or "tenor," the "vehicle," and the "ground") and a theory of how metaphors function. This theory, called the tensive view, emphasized the conceptual incompatibility, or "tension," between the terms (the topic and the vehicle) in a metaphor (Ortony, 1993). Black's interpretation of metaphor, referred to as the interaction model, claims that metaphor is a cognitively irreducible phenomenon that works not at the level of word combination, but much deeper, arising out of the interactions between the conceptual structures underlying words. In comparing two concepts, the significance of one concept is not merely projected onto another, but the two interact, altering the perception of both concepts. Explaining this theory in metaphorical terms, Black offers the following analogy (1962):

> Suppose I look at the night sky through a piece of heavily smoked glass on which certain lines have been left clear. Then I shall see only the stars that can be made to lie on the lines previously prepared on the screen, and the stars I do see will be seen as organized by the screen's structure. We can think of the metaphor as such as screen and the system of 'associated commonplaces' of the focal world as the network of lines upon the screen.

In his theory, Black claims that the following are true of all metaphors (synopsis from Ortony, 1993):

- Metaphors consist of primary and secondary components. (In the statement "*X is like Y" X* is referred to as the primary and *Y* the secondary. Other literature refers to these as the tenor, vehicle, target, etc., and there is no standard convention across disciplines. I will use *base* and *target*, recognizing that these make implications about the nature of analogical reasoning.)
- The significance of the base subject is not so much as a "thing" as it is a system.
- The associated implications of the base are projected onto the target.
- This projection selects, organizes, emphasizes and suppresses features of the target component. Through this interaction of the two subjects there is a selection of properties, an implication on the target, and, reciprocally, an implication back on the secondary.

This interpretation of metaphor, which is still central to many theories of metaphor, was incorporated four years later by Mary Hesse, a philosopher of science, whose "treatise on analogy in science argued that analogies are powerful forces in discovery and conceptual change" (Holyoak, Gentner and Kokinov, 2001). This treatise, *Models and Analogies in Science* (1966), argued that "the deductive model of scientific explanation should be modified and supplemented by a view of theoretical explanation as metaphoric redescription of the domain of the explanandum." Additionally, she coins three new terms in analogical reasoning: the positive, negative and neutral analogies. In positing an analogy, "positive analogies" are known to transfer from the base to the target, "neutral analogies" are possible elements of the base that are present in the target, and "negative analogies" are elements that do not transfer.

Analogies in cognitive science

In the 1980's, concurrent with Lakoff and Johnson's work on metaphor, there was a shift in research from four-term analogies (of the type found in standardized tests – a:b::c:d) to more complex analogies, such as those found in science and language. According to Holyoak, Gentner and Kokinov (2001), who were themselves pivotal in this shift,

> This exploration led to a more general focus on the role of experience in reasoning and the relationships among reasoning, learning, and memory, giving rise to an approach termed " case-based" reasoning (e.g., Kolodner 1993). In contrast to rule-based approaches to reasoning (the approach that was dominant in AI at the time), case-based reasoning emphasized the usefulness of retrieving and adapting cases or analogs stored in long term memory when deriving solutions to novel problems.

This work continued to adopt Black's model of metaphor, most significantly the system of relations in the base of the analogy. Among the best-known models developed at this time is Gentner's theory of structure-mapping (1983). In this model

> the central idea is that an analogy is a mapping of knowledge from one domain (the base) to another (the target) such that a system of relations that holds among the base objects also holds among the target objects. In interpreting an analogy, people seek to put the objects of the base in one-to-one correspondence with the objects of the target so as to obtain the maximal structural match… Thus, an analogy is a way of aligning and focusing on relational commonalities independently of the objects in which those relations are embedded. (Gentner and Jeziorski, 1993.)

From this model a computational model, the Structure Mapping Engine, was developed by Falkenhainer, Forbus and Gentner (1990). Holyoak and Thagard (1989) have a similar (ACME) program for analogies that is instead based on a connectionist network, but the underlying model of analogy is the same. It is important to note that these models will take two systems (for example, the solar system and the Rutherford model of the atom) and, as Falkenhainer, Forbus and Gentner (1990) describe, construct "matching algorithms consistent with [the] theory."

In contrast to these models are those posited by Douglas Hofstadter and the Fluid Analogies Research Group (FARG) at Indiana University, beginning with Melanie Mitchell's (1990) dissertation. Their computational models do not interpret a given analogy, but generate novel analogies. These models, Copycat, LetterSpirit and Metacat, are based on the thesis

> that mental activity consists of many tiny independent events and that the seeming unity of a human mind is merely a consequence of the regularity of the statistics of such large collections of events. Thus the metaphor of the "intelligent ant colony" and the image of "active concepts"…have inspired our models for over two decades. The models all involve the nondeterministic interaction of many tiny events that take place in simulated parallel. The models also feature both long-term and short-term memories, the former of which houses permanent concepts, and the latter of which is like a stage on which temporary mental structures are built, modified, and eventually razed. Events in each memory profoundly influence the multiple tiny parallel processes, and in that way, each memory affects what goes on in the other. (Hofstadter, 2004)

This thesis concerns itself with the creation of analogies, as opposed to their interpretation. I will show in later chapters that structure-mapping cannot account for analogy creation, and argue that the Hofstadter's interpretation of cognition as "many tiny independent events" is consistent with modern views on categorization, which are consistent with observed properties of student-generated analogies in science.

Analogies in linguistics

Concurrent with this shift in cognitive science (and, in particular, artificial intelligence) from rule-based to case-based reasoning, the field of linguistics began a departure from traditional Chomskian emphasis on linguistic competence towards "an increasing concern with linguistic performance and pragmatics" (Ortony, 1993). Representative of this shift is Lakoff and Johnson's *Metaphors We Live By*. In this book the authors argue that our ideas are not only referred to linguistically through metaphors (defined by the authors as "understanding and experiencing one kind of thing in terms of another") but also actually conceptualized in metaphorical terms. The choice of a secondary subject in these metaphors is one that allows the speaker to conceptualize "the nonphysical *in terms of* the physical – that is, we conceptualize the less clearly delineated in terms of the more clearly delineated… the prime candidates for concepts that are understood directly are the simple spatial concepts, such as UP." This claim is evident in physics, where we speak of high and low potentials and energy and conceptualize atomic forces as wells.

> As our choice of metaphor will reflect our conceptualization of the phenomena, our metaphorical choice may change depending on the context of the problem. Consider the following statements, "Light consists of particles" which apparently contradicts "light consists of waves," but both are taken as true by physicists relative to which aspects of light are picked out by different experiments. (Lakoff and Johnson, 1980)

There is enormous utility in being able to conceive of light in different ways – to categorize light as a particle or as a wave. As Lakoff and Johnson state (1980),

> understanding our experiences in terms of objects and substances allows us to pick out parts of our experience and treat them as discrete entities or substances of a uniform kind. Once we can identify our experiences as entities or substances, we can refer to them, categorize them, group them, and quantify them – and, by

> this means, reason about them. When things are not clearly discrete or bounded, we still categorize them as such, e.g. mountains, street corners, hedges, etc.

That is, there is a relationship between these categories and metaphorical language: our language, which Lakoff and Johnson demonstrate is profoundly metaphorical, allows us to categorize phenomena.

Analogies in general, and metaphors in particular, are a topic of widespread interest and debate in linguistics at this time. Some of these debates will be further reviewed in later chapters. For a more complete review, see *The Analogical Mind* (Gentner, Holyoak and Kokinov, 2001).

Analogies in science and science education

> …I think it would also be practical to design a curriculum based on an inquiry into the use of metaphor. Unless I am sorely mistaken, metaphor is at present rarely approached in school except by English teachers during lessons in poetry. This strikes me as absurd, since I do not see how it is possible for a subject to be understood in the absence of any insight into the metaphors on which it is constructed. All subjects are based on powerful metaphors that direct and organize the way we will do our thinking.
>
> -Neil Postman, *Conscientious Objections: Stirring up Trouble about Language, Technology, and Education*

A significant feature of the existing research on the role of analogies in instruction is that the focus has been on analogies drawn by the teacher and explained to the students. Research paradigms for constructing and testing models of analogical reasoning have similarly focused on the comprehension of analogies that have been created by the researcher. Very little work has looked at generated analogies. This paradigm is indicative of a tradition of science education in which the students are interpreting instruction from the teacher, and not discussing and debating their own views of science. As reforms in science education call for greater attention to student ideas and student reasoning, the existing theories on analogy interpretation are of less use and there is a greater demand for understanding analogies as they are generated. Here I provide a brief overview on the research on the role of analogies in the classroom, the role of analogies in science, and the disconnect between what scientists do and what is attended to in classrooms.

In a pioneering work on scientific analogies in instruction, *Flowing Waters or Teeming Crowds: Mental Models of Electricity* (Gentner and Gentner, 1983)*,* students were given instruction in circuits using one of two different analogies: one visualized the flow of current as a crowd of electrons, one a flowing water-like substance. (Experts use both models to represent different features of current.) Tests given post-instruction were designed to test whether analogy is an important source of insight (the Generative Analogy hypothesis) by "asking whether truly different inferences in a given target domain are engendered by different analogies" (Gentner and Gentner, 1983). The answers that students gave were overwhelmingly representative of the analogical model they had been taught.

Clement's work in physics education has focused extensively on analogical reasoning in the physics classroom, with attention primarily on explicit analogies generated by teachers and interpreted by the students. In Clement (1992), he describes "bridging analogies." These analogies are instantiated by the teacher and are used to motivate the students to see a likeness between two phenomena (say, the force provided by a spring supporting a book and a similar force from a table supporting a book) by providing intermediate analogies (a tight spring, a flexible board). The idea that a student will recognize "A is like B" and "B is like C" but not recognize that "A is like C" without explicit instruction supports a model of categorization in which “family resemblance” to the category prototype defines the membership of the category. In this way, prior research on analogical reasoning can facilitate the link between analogies and categorization. In the following section I will provide an overview on research into categorization.

More recent research on the role of analogies in physics continue in the paradigm of instruction by analogy:

Taber, in *When the Analogy Breaks Down: Modeling the Atom on the Solar System* (2001), notes that: “Analogy is one of the most potent tools in a teacher's repertoire and has been recognized as a common feature of quality science teaching.” He voices concerns regarding the utility of a solar-system model of the electron and the students’ lack of knowledge regarding the solar system in drawing such an analogy.

Mould (1998) is one of many instructional analogies that are frequently introduced in *Physics Education.* In this article, he suggests the use of an analogy to resolve the puzzle of the lost energy when two capacitors are joined together by comparing this scenario to the concept of water flowing between two tanks.

Harrison and Treagust (1999) have explored the relationship between the analogies we tell our students and the models students construct from these analogies, arguing that “students do not interpret scientific analogical models in the way we intended” and investigate potential factors in the consistency of analogy use in models of atoms.

Notable exceptions to investigations on teacher-generated, didactic analogies include Duit, Roth, Komorek and Wilbers (2001) who “studied analogy generation and development and analogical reasoning with 25 German tenth graders in a physics class. Results show the advantages and disadvantages of using analogies in promoting conceptual change and as a teaching technique." Their focus, however, was on the utility of analogy in conceptual change and not the generation of analogy as a goal in itself. And Yerrick, Doster, Nugent, Parke and Crawley (2003) who investigated the role of analogies in pre-service teachers' conversations and argue for analogy as part of preservice teachers' conceptual development.

Turning to the role of analogy in science, and not just the science classroom, Dunbar (2000, 2001) has conducted research on "in vivo analogies," going to research groups and listening to the ways in which they use analogies and analogical reasoning in their work and discourse. Analogies, he finds, are "frequent in science and in all aspects of human thinking." They are ubiquitous and crucial to the ways experts reason about science. One goal of science education could be considered to develop habits and skills that scientists employ in scientific reasoning. The focus in the literature on analogies as a means of arriving at correct conceptual understanding ignores the import of developing analogical reasoning as a skill to be mastered in and of itself. As May, Hammer and Roy (2004) noted, "inasmuch as expertise at inquiry supports… students and scientists developing conceptual understanding, young children's development of understanding and abilities for analogical reasoning will serve them better than learning the content knowledge of an expert."

Summary of analogy research

The main theme from this research that I will address is that the majority of research on analogies, and educational analogies in particular, has concerned how people interpret analogies and not on the creation of analogies and its implications on mental models of concepts. If analogical reasoning is an important feature of scientific reasoning, then one goal of science education should entail fostering the use of analogies and developing students' abilities in this realm. As educational researchers, understanding analogical reasoning, what assertions analogies make, what they reveal about the mind, are of importance – *not* because such findings allow us to better convey content, but because they inform us about a skill that is, in itself, one we should foster in our students.

Categorization

Overview

> Categorization is not a matter to be taken lightly. There is nothing more basic than categorization to our thought, perception, action, and speech, Every time we see something as a *kind* of thing, for example, a tree, we are categorizing. Whenever we reason about *kinds* of things – chairs, nations, illnesses, emotions, any kind of thing at all – we are employing categories. Whenever we intentionally perform any *kind* of action, say something as mundane as writing with a pencil, hammering with a hammer, or ironing clothes, we are using categories.
>
> -George Lakoff,
> from *Women, Fire and Dangerous Things*

In 1987, George Lakoff published *Women, Fire, and Dangerous Things: What Categories Reveal about the Mind*. This work thoroughly summarizes the research on categorization up to that time and interprets the philosophical implications of these findings. Rosch, who tied together existing research on categorization and created an experimental paradigm for investigating categorization, began from the opposite end – she received her undergraduate training in philosophy and brought this to bear on psychology. Her honors thesis was on Wittgenstein's 1953 treatise, *Philosophical*

Investigations (Scharmer, 1999), a work that is credited with “the first major crack in the classical theory [of categorization]” (Lakoff, p16).

The classical view of categories held that there were rules of membership and if an item met these rules then it was a member of the category (or, there are properties that define a category and all members must share these properties). In this view categories, therefore, were seen as binary with no internal structure: an item either was or was not a member of that category, and the research paradigm for categorization was to define the rules or properties. Wittgenstein’s work addressed the fact that certain categories, such as “game,” do not fit this classical description. There is no one property that all games share, but rather there are family resemblances between games, so that “chess and Go both involve long term strategy… chess and poker both involve competition. Poker and old maid are both card games” (Lakoff, 1987 p. 16). Additionally, these categories had no fixed boundary – they could be extended and redefined as new games are introduced, or as previous games shift their context. About this time, a similar recognition of inconsistencies in our conception of categories occurred in mathematics.

Categorization and fuzzy sets

In mathematics, the analog of a linguistic category is the set. In classical set theory an instance either belongs to a set or it does not; there is no middle ground. An item’s membership in a set is determined by whether or not it has the properties that define that set, called the class intension. For example, if the set is the class of all objects that are green, the intension of that set is the property green. This clean definition of the set allows for simple rules to be associated with them. The set of objects that are either green or square is the union of the sets of green objects and square objects. The set of all things that are green and square is the intersection of the sets of green objects and square objects. However, a complication associated with set theory occurs at the border between the set and non-set. For an intension that splits the set of all objects in two, such as greenness, items will either belong to the set of green objects, or to the set of non-green objects, but there is an ambiguity for items that falls at this boundary between green and not-green. Applying this simple mathematical structure of sets to human-created categories does not work. There is logical inconsistency in assigning such items to both sets and to neither set. And the commonly accepted solution to this problem is the "law of excluded middle," which simply forbids there being an object that falls exactly at the border of set and not-set. Zadeh (1965) saw this solution as indicative of the fact that classical set theory does not capture the way in which we experience the world. Things come in gradations: some animals are birds, and some animals are mammals, while some, like the platypus, with its bill, webbed feet and fur, seem to fall somewhere in between. Statements are not always either true or false. The standard solution to the incompatibility of set-theory sets and human categories is to claim that mathematics, with its rigid structure and well-defined systems, does not apply to many real-world problems. Zadeh's solution was to allow for gradual sets and "fuzzy logic." The amendment he made to standard sets was to allow membership in a set to be a non-binary concept, and then extend the operations on ordinary sets to account for this allowance. If an element x has membership in set A with value v and in set B with a value w, then the operations on sets are adjusted in the following way:

Intersection: The value of x in $A \cap B$ is the minimum of v and w.

Union: The value of x in $A \cup B$ is the maximum of v and w.

Complement: The value of x in the complement of A is $1-v$.

This theory allows for a category of "P and not P" – for example, the category defined by "an apple that is not an apple." The crabapple and Adam's apple are both judged to be members of this category. Zadeh's fuzzy set theory reflected a change in the conception of categories that had been developing in anthropology.

Rosch and prototype theory

About the same time, anthropologists, influenced by the Whorfian hypothesis (1956), assumed that color categories were arbitrary and different languages could carve the color spectrum in different, arbitrary ways. However by the late 1960's it was found that, though different languages do vary in the number and kinds of colors they name, there is regularity in color categories among different cultures (Berlin and Kay, 1969). Speakers of different languages that disagree on color category boundaries will agree on which colors were good examples of these categories. Rosch, who was conducting research on the Dani in New Guinea, began looking at their color categories. She depicts the prior research on categorization in this way:

> When psychologists did research on concept learning, they used artificial concepts and sets of artificial stimuli that were constructed so that they formed little micro-worlds in which those prevailing beliefs about the nature of categories were already built in. Then they'd do their learning experiments. But what they found out in terms of the nature of categories was already a foregone conclusion because that was what they had already built into it (Scharmer, 1999).

Rosch argued that, because of the way the perceptual system works, certain areas in the color space are more salient than others, and that those salient colors are first noticed, most easily remembered, and become prototypes around which color categories form in cultures. The Dani had only two basic color terms, dark and light, making this culture ideal for testing the hypothesis. By teaching them novel color categories, structured around natural and unnatural color schemes, Rosch found that the Dani remembered the hypothesized "universal prototype" colors better than other colors, and it was much easier to learn categories structured around those colors than categories structured some other way. Further research extended this to shapes and other categories, and supported her thesis that

> categories form around and (or) are mentally represented by salient or information rich or highly imaginable stimuli which become prototypes for the category. Other items are judged in relation to these prototypes; that's the way they form gradients of category membership. There don't need to be any attributes which all category members have in common, no defining attributes, and category boundaries don't need to be definite (Scharmer, 1999).

In the research that followed, Rosch (1975) showed that certain category members were judged to be better examples of the category than others. A robin is judged to be a better example of the set birds than a penguin, although, strictly speaking, both are birds. This psychological rendition of Zadeh's fuzzy set theory established fuzzy logic as an important component of AI research. In addition, Rosch's research established experimental paradigms for investigating categorization, attending to features such as the following (using the category "bird" for illustration):

- Direct rating. (How birdlike is this?)
- Reaction time. (Show a picture and ask: Is this a bird?)
- Producing an example. (Draw a bird.)
- Asymmetry of similarity. (Are ducks like robins? Are robins like ducks?)
- Asymmetry of generalization. (Robins get the flu; do ducks? Ducks get the flu; do robins?)

In this paradigm, a prototype will receive a high rating, low reaction time, and resembles the example produced. From this research, properties of categories were determined. These are detailed in the following section.

Properties of categories

It was readily apparent that the structure of real categories, as researched by Rosch and others, was not consistent with the classical view. Categories, which in the classical view were devoid of any internal structure, were shown to possess both centrality gradience (the idea that some categories have members that, though clearly within the category boundaries, are more or less representative of the category) and membership gradience (the idea that some categories have degrees of membership, so that the distinction between member and non-member, the category boundary, is not clear). Members of many categories were related to one another in a "family resemblance" manner, so that no one property is common among all members. The structure of categories leads to "a basic psychological asymmetry: the less prototypical category member is conceived of as closer (i.e., more similar) to the more prototypical member than vice versa" (Shen, 1999). People will more readily compare a non-prototype to a prototype and will more likely generalize from the prototype to the non-prototype than vice versa (Rips, 1975). There is a primary level of categories, known as the basic level, that are "primary with respect to the following factors: gestalt perception, image formation, motor movement, knowledge organization, ease of cognitive processing, and ease of linguistic expression" (Lakoff, 1980). The most central members of a category can function as metonyms for that category – a property common to many languages. For example, American Sign Language has no sign for the category *jewelry* and in ASL this category is referred to by listing the prototypical members (Newport and Bellugi, 1978 p 62); the Hopi call all trees "cottonwood," the name of the most common deciduous tree in their habitat (Trager, 1936-9); Shoshoni speakers refer to large birds in general as well as to eagles themselves as eagles (Hage and Miller, 1976).

From this data, initial theories on categorization argued for interpreting category membership and structure as degree of similarity to the category prototype. However, further work showed that categories are not defined solely by family resemblance to a prototype, but have an intellectual and ecological basis. Barsalou's (1983) studies of "ad hoc" categories, categories that cannot be interpreted as fixed cognitive structures, such as "foods not to eat when on a diet," or "things to do at a convention," found that members of these categories retain the graded structure and typicality effects that Rosch found. However, these categories did not necessarily show a family resemblance to the prototype. Instead, Barsalou argues, these categories are goal-oriented; a chocolate cake has little resemblance to peanut brittle, but abstaining from these satisfies the goal of eating as few calories as possible. Similarly, research was beginning to reveal that similarity alone could not account for even the more typical, stable categories. For example, "the claim that something is a *dog* does more than assert some degree of similarity to a prototype; it also appeals to our underlying intuitions and beliefs about the nature of animals. The effect of these beliefs is to make some similarities between objects decisive and others simply irrelevant" (Neisser, 1987 p3). The claim that similarity alone is an explanation, according to Goodman (1972), is "a pretender, an imposter, a quack. [Similarity] has, indeed, its place and its uses, but is more often found where it does not belong, professing powers it does not possess." In Murphy and

Medin's (1985) paper, "The Role of Theories in Conceptual Coherence" they argue against similarity arguments, claiming that

> Current ideas, maxims, and theories concerning the structure of concepts are insufficient to provide an account of conceptual coherence. All such accounts rely directly or indirectly on the notion of similarity, and we argue that the notion of similarity relationships is not sufficiently constraining to determine which concepts will be coherent or meaningful. These approaches are inadequate, in part, because they fail to represent intra- and inter-concept relations and more general world knowledge. We propose a different approach in which attention is focused on people's theories about the world.

The argument entails that

> categorization assumes a (folk) theory on the part of the person who is engaged in that particular cognitive process. This theory 'guides' him in selecting the relevant features and the relevant feature correlations; in other words, noticing features and feature correlations is not an 'objective' process based on similarity, but is instead theory-dependent." (Shen, 1992)

The effect of these findings is to make some similarities between objects decisive and others irrelevant. With these and other findings, Rosch eventually

> came to the conclusion that prototype effects, defined operationally by experiment, underdetermined mental representations. The effects constrained the possibilities for what representations might be, but there was no one-to-one correspondence between the effects and mental representations. The effects had 'sources,' but one could not determine the sources given the effects. (Lakoff p 43)

An alternative to prototype theory is described below.

Idealized cognitive models

As a theory to explain the prototypes that Rosch first documented, Lakoff, in *Women, Fire and Dangerous Things* claims that "prototype effects result from the nature of cognitive models, which can be viewed as 'theories' of some subject matter." (p. 45) Lakoff terms these models "idealized cognitive models," or ICMs, and suggests that, to the degree to which the model does not represent reality, these ICMs will lead to categorization and prototype effects. A classic example from linguistic research of categorization, prototype effects and gradience of membership in a category is the term *bachelor* (Fillmore, 1982). While most people will define a bachelor as an unmarried adult male, certain unmarried adult males are not representative members of the category of bachelors. Lakoff (1987) argues that

> *bachelor* is defined with respect to an ICM in which there is a human society with (typically monogamous) marriage, and a typical marriageable age. The ideal model says nothing about the existence of priests, "long-term unmarried couplings," homosexuality, Moslems who are permitted four wives and have only three, etc. With respect to this ICM, a *bachelor* is simply an unmarried adult man.

This idealized model, however, does not fit the world very precisely. It is oversimplified in its background assumptions. The person referred to deviates from prototypical bachelorhood if either the ICM fails to fit the world perfectly or the person referred to deviates from being an unmarried adult male.

> Under this account bachelor is not a graded category. It is an all-or-none concept relative to the appropriate ICM. The ICM characterizes representative bachelors. One kind of gradience arises from the degree to which to ungraded ICM fits our knowledge (or assumptions) about the world. (Lakoff, 1987)

ICM's can closely match the world, in which case the categories that you developed to create this ICM are robust categories with little gradience. The idea of the ICM has been further parsed and is perhaps best represented by schema theory. Schemas are short "scripts" or stories that we have about the world and the way it works: *event schemas* that are abstracted from our experience of certain events, *image schemas* that provide structure for conceptualizations – "schemas of intermediate abstractions [between mental images in abstract propositions] that are readily imagined" (Palmer, 1996 p. 66) – and *proposition schemas*: abstractions that act as models of thought and behavior and specify "concepts and the relations which hold among them." (Quinn, 1987) It is only within a particular schema that a category is meaningful, and these categories become les meaningful and exhibit a graded structure to the degree that the schema in which they are defined does not apply. A claim of analogies as assertions of categorization then entails analogies as instantiations of particular schemas.

Metonymy, cognitive models and phenomenological-primitives

Phenomenological primitives (p-prims) (diSessa 1993) were developed to address the "preconceptions" of students in problem solving in physics. They are "the intuitive equivalent of physics laws; they may explain other phenomena, but are not themselves explained with the knowledge system." As defined by diSessa, p-prims are "cued to an active state on the basis of perceived configurations, which are themselves previously activated knowledge structures." In this way p-prims are elements within larger models. P-prims "often originate as minimal abstractions of common phenomena," and are "nearly minimal memory elements, evoked as a whole." By way of example, consider one class of p-prims: the "constraint cluster." This class includes bouncing, supporting, guiding, clamping, and carrying. These p-prims are not fundamental for a physicist (all can be explained in terms of forces) but are often elicited in conversations with students as explanations for physical behavior. The p-prims have a "schematization" such as, for the "supporting" p-prim, "'strong' or stable underlying object keeps overlaying and touching object in place." (diSessa, 1993 p. 216)

That a p-prim has a full schematization but is often represented only partially by a particularly salient feature of the schema (e.g., "supporting" as an explanation entails two objects, one of which is strong or stable and underlies another object which touches it) is indicative of the schematization of a p-prim being an idealized cognitive model. This single salient feature of the schema is what Lakoff refers to as a metonym for the idealized cognitive model. Lakoff presents the following example to explain metonymy is the context of ICMs (Lakoff, 1987):

> A linguist who does fieldwork on Ojibwa, a Native American language... asked speakers of Ojibwa who had come to a party how they got there. He got answers like the following (translated into English):
>
> -I started to come.
> -I stepped into a canoe.
> -I got into a car.
>
> He figured out what was going on when he read Schank and Abelson's *Scripts, Plans, Goals, and Understanding* (1977). Going somewhere in a vehicle involves a structured scenario (or, in our terms, and ICM)... In Ojibwa it is conventional to use the embarcation point of an ICM.

That is to say, the embarcation point is a metonym for the entire structured scenario, or ICM. English, too, uses a point of the journey to refer to the whole. Typical English responses to the question of “How did you get here?” may be: “I have a car,” or “I biked.” Neither comment conveys the entire journey, but chooses one part to represent the whole. This is only possible because we have a model for the journey, and one part can, metonymically, elicit the whole. In the same way, phenomenological primitives as explanations for physical phenomena are only possible because of a larger schema.

The claim I will make, that the p-prim and schema precedes or is in some way more fundamental than the analogy itself, is echoed in diSessa’s studies involving the “Montessori bell conundrum.” In this problem, students are presented with bells made of the same material, same length, same height, but varying widths. Almost without exception students predict (erroneously) that the thicker bells will have a lower pitch. DiSessa reports:

> Although most subjects were ready with analogies – church bells compared with jingle bells, xylophones, musical instruments of various sizes – I was struck that some initially could not produce any example of the phenomenon they identified to be at the root of the situation. This, along with the rapidity and expressed certainty of responses, heightened my confidence that a p-prim (or several) was at stake rather than analogy.

In following chapters, I will present data that argue that generated analogies stem from a set of schemas or p-prims.

Summary of categorization research

The main points I will be taking from categorization research are the established properties of categories (including graded structure, asymmetry of generalization, prototypes, family resemblance, and metonymy), that categories can be considered *ad hoc* constructions (and still retain the characteristics of a category), that theories, expectations and goals underlie our construction of some categories, and that graded structure in categories is a reflection on the degree to which these theories match the "real" world.

Analogies as Categorization

Metaphors as category-inclusion statements

Consider the following statements, one typically considered categorization and the second analogy:

1. This ball bearing is a mass.
2. In circuit with an inductor, capacitor and resistor, the inductor is like a mass.

The first is a statement that the ball bearing is a member of the category "mass." The second, however, is not a statement that the inductor is a member of that category, but, I argue, by drawing the analogy we are suggesting that the inductor and that the members of the "mass" category share some categorical grouping in common. One could characterize that category "things which slow the rate of change" (this characterization is referred to as a "ground" in a metaphorical comparison). This category is rarely referred to and therefore is not a stable category with its own name, but more of the *ad hoc* type category that Barsalou (1983) introduced – a spontaneously constructed category that is structured by theories or goals. Glucksberg and Keyser (1990) were the first to identify this relationship and have argued for interpreting metaphorical assertions as categorical assertions, claiming that

> When people use metaphors, they *are* saying exactly what they mean. When, for example, someone says that "Sam is a pig," that is precisely what is meant; that the person designated by the name "Sam" is a member of the superordinate category referred to by the word "pig."

Glucksberg and Keyser argue that the choice of the secondary subject in a metaphor (*pig* in "Sam is a pig") reflects a tendency of languages to have names for basic level objects but not for superordinate categories. Such examples can be seen in the English language, as in the aphorisms "Boys will be boys" or "Cambodia has become Vietnam's Vietnam" (or, as mentioned recently in the 2004 election, "Florida does not want to be the next Florida). These expressions use a "single referring expression… in two distinct ways, to allude to the entity itself and to refer to the category… that this entity has come to exemplify" (Glucksberg and Keyser, 1990 p. 411). (For example, "eagle" in Shoshoni and "cottonwood" in Hopi, as mentioned in a previous section.) When the base of an analogy (termed the vehicle in the context of metaphor) is used as both an exemplar and as an ad hoc name for a category, Glucksberg et al. (1997) call this linguistic move "dual reference." As an example of dual reference,

> the phrase “a responsibility is a shackle” can be used to refer to the concrete, physical device that is made of metal, often has chains, can be locked around someone’s arms and legs, and so forth, and it can also be sued to refer to the abstract, general category of constraining entities. We refer to such abstract, general concepts as attributive categories. (Glucksberg et al, 1997 p. 334)

The authors claim that “nouns can be used to make dual reference whenever a superordinate category has not been lexicalized and a category exemplar is available that is prototypical of that category.”

Glucksberg and Keysar continue with the assertion that metaphor is not a literal comparison, and must be considered property attributions that extend or create categories. As an example, they contrast the literal comparison with the metaphorical:

> “Copper is like tin”… cannot be paraphrased as category assertions and still make sense, for example, … “Copper is tin.”
> Thus the paradox: Two unlike things compared can be paraphrased as a categorical assertion, whereas two like things compared cannot. This paradox may hold the key to a fundamental difference between literal and metaphoric comparisons. We argue that metaphors are not understood as comparisons, but rather as property attributions that either extend old categories or create new ones.

I hold that the difference in these statements is a result of what Roger Brown originally described: “Metaphor differs from other superordinate-subordinate relations in that the superordinate is not given a name of its own. Instead, the name of one subordinate is extended to the other” (Brown, 1958). “Tin” is not a name for the category of which they are members (owing to the fact that this category has a name and that tin is not a prototypical member) and “jail” is (because this category, as it is less stable, has no name and is referred to by its most prototypical member). Furthermore, placing tin and copper in the same category is *expected* and does not violate any previously held ontology or necessitate the construction of a new, ad hoc category, unlike placing jobs and jails into the same category. And, as Barsalou (1983) has shown, ad hoc categories have the same structure and properties as traditional categories. The difference, then, between a metaphorical comparison and a literal one may have cognitive importance in terms of stability of the category and conceptual coherence, but not in terms of the conceptual structure. Shen's (1992) *Metaphor and Categories* makes similar claims as Glucksberg and Keysar. He argues that "in interpreting a metaphorical comparison, an ad hoc category is constructed so that the two metaphorical terms are conceived of as its members," and that the secondary term in a metaphorical statement is typically "a prototypical member of that category." Shen, too, makes a distinction between literal comparisons and metaphorical comparisons, claiming that a literal comparison is indicative of a "common" category, while ad hoc categories are represented by metaphorical comparisons.

Traditionally, metaphors have been interpreted as statements of similitude and not categorization because of the assumption that words (such as "pig" when claim that the person "Sam is a pig") refer to specific taxonomy. Studies on how our *minds* perceive of words and how these perceptions are related to taxonomic definitions versus metaphorical relationships are detailed in the following section.

Idealized cognitive models and lexical networks

Eve Sweetser's 1984 tests of the definition of "lie" (as in "to tell a lie"). She points out that, while most people define a "lie" as "a false statement," in practice:

> A consistent pattern was found: falsity of belief is the most important element of the prototype of *lie*, intended deception the next most important element, and factual falsity is the least important.

These findings are consistent with the idea that humans conceive of the world using idealized cognitive models and that the imperfection of these models results in a graded structure of categories. In the “lie” example the ICM being employed is a model of communication, as studied by Grice (1975). Grice removed the study of language from its Chomskian position of mathematical clarity and tied it to the study of communication arguing that, in order to understand the way language works, one must understand expectations that exist in communication. These expectations (the idealized cognitive model of communication) entail clarity, truth, information, and relevance on behalf of the speaker and influence our expectations for the definitions of words.

If words, such as “lie” are not used in a manner consistent with the definition one would find in a dictionary, how are words represented in the mind? Recent psycholinguistic theory has suggested that the mental lexicon, instead of being organized in a dictionary-style, is far more like a thesaurus. That is to say, the way our minds perceive of words is not so much as obeying rigid definitions with propositional structure, but rather the meaning of one word is tied to a network of related words – words that have appeared in similar contexts, words that have appeared in context with that word, and words that have related meanings. Computationally generated lexical networks have been developed to represent the lexical network of the English language as expressed in dictionaries (one example is the well-known Wordnet (Fellbaum, 1998)). These thesaurus-like structures link words in definitions into a network using various algorithms. Gaume et al. (2002), building on categorization research that they summarize as establishing the “conceptual flexibility” as opposed to “rigid and discontinuous categories,” argue that words *themselves* constitute categories and contend that these lexical networks weave a “mental lexicon distributed around metaphoric poles.” In this regard, dictionary definitions of terms such as “lie,” “pig,” and “boys,” especially in the contexts noted above, can be expected to fall short of the full meaning of these terms as used in regular language. When these terms are expressed in a lexical-network sense, they can be viewed as representing categories of characteristics or qualities, rendering the metaphorical statements, such as "he's a pig" and "boys will be boys," as assertions of class-inclusion as Glucksberg and Keysar (1992) have argued.

Reconciling categorization and structure-mapping views of analogies

To address the ideas raised by Glucksberg and Keysar and reconcile these with Gentner's structure-mapping theory of analogy, Bowdle and Gentner describe a "path in figurative language comprehension" that claims that there is a shift in the method of comparison in figurative language. Novel metaphors, they claim, are interpreted via a structure-mapping mechanism, while conventionalized metaphors – words that have an original meaning that is different from an often-used meaning (e.g., "roadblock" or "goldmine") – are interpreted as categorization. The issue of *comprehension* of metaphor is not at the heart of this thesis: what someone means when they make a novel analogical statement has to do with the creation of an analogy. It is reasonable, however, to expect that understanding a conventional metaphor might be a similar process to creating your own metaphor: in both cases the categorical commonalities (the ground of the category) is known, while interpreting a novel metaphor would require a "search" of possible meanings of the secondary subject that are being implied.

Conclusion

Words, such as "lie" and "pig," have definitions that exist in a dictionary – stable definitions that people will readily agree on as sensible. These definitions possess a rigid propositional structure, so that "pig" is thought to mean "pink animal with a snout" and “lie” is defined as “an untrue statement.” But these definitions are only valid when you accept a certain model about the ways in which we communicate. When you take into account that communication is not so straightforward as our idealized cognitive models of language assume, pinning down the exact description or definition of a word, such as “lie” or “pig,” is a much more difficult endeavor – more context dependent and slippery. Lexical maps, which link related terms into a network, more closely approximate the lexical structure (or dictionary) of our minds. Accepting this about language has implications for the interpretation of analogical statements: traditionally, an analogical statement is not literal because the base of the analogy is not intended to be interpreted literally. Instead, I argue that analogical statements are assertions of categorization, and the difference between analogy and traditional categorization is that analogies violate an expected ontology and may even necessitate the construction of a new, ad hoc category. To say that “Sam is a pig” demands that you consider the nodes in the “pig” lexical network that could possibly relate to Sam (including muddy, slovenly, lazy, messy) – just as when one says “I eat pig” (typically viewed as a non-metaphorical statement, but one which calls up the pork chop, ham, and sausage aspects of the pig lexical network). The difference lies in that “pig” is defined in the cognitive model that allows for this animal as distinct from others and “Sam is a pig” requires you to “turn off” some parts of the network.

In the following chapters I will argue that generated analogies in science are statements of category-inclusion that violate the expected categorization of the target. When a student asserts that a cup of water is like a cat in a basket, she is constructing an ad hoc category, this category is intimately tied to a theory and cognitive model, is derivative of this model, and that the secondary item in the analogy is a prototype of this ad hoc category. Furthermore, these categories and their structure are indicative of an underlying idealized cognitive model – ones that are often metonymized by phenomenological primitives. This interpretation of analogies is responsive to findings from cognitive science, linguistics and education that argue for a manifold ontology of mind.

Chapter 3: Origins of the Study & Methodological Considerations

Origins of the Study

The following passages are taken from a "Science Talk" (Gallas, 1995) in 5th grade classroom in rural Maryland. It is early November and the science resource teacher, Bruce Booher, has come to lead a discussion. The students have worked with Mr. Booher in the past and this format of science instruction is not unfamiliar to them. The question that he has chosen comes from an experiment suggested on a NASA website regarding zero gravity. The students are posed the following question (NASA, 1999): a cup full of water is inverted on a cookie tray and the tray is rapidly pulled out from underneath the cup (see Fig. 3.1). What happens to the cup-water system? The students will later observe that the water does not leave the cup as it falls to the ground – the cup falls at the same rate as the water and the water will only spill out once it reaches the ground. Most students, however, believe the water will "go everywhere," "spill," or "splash" as the tray is removed and report as much. Their answers do not give any rationale or mechanism by which this will happen. However, one student predicted the correct outcome and explained her prediction with a spontaneous analogy (transcript 2, lines 8 – 36).

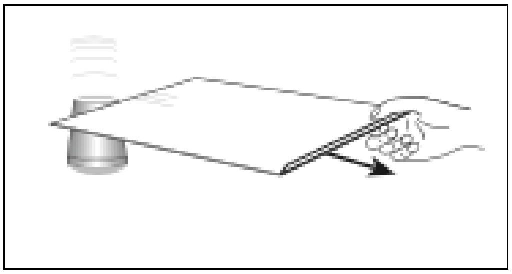

Fig. 3.1: The Experiment: A tray pulled out from under a cup

Teacher: …let's see what some– I see a lot of other hands up. Um, Miranda?

Miranda: I predict that when it falls off it's going to stay in the cup until it gets down to the floor and then it'll splash.

Teacher: So you have a prediction that when I slide it off of the tray the water is going to stay in the cup. Now that's very different from what they're saying.

Miranda: 'Cause at home when I have like something in a basket and when I go like that real quick [student swings arm around, miming that the basket is swung overhead and quickly pulled down] it stays in. So when – and when I pull it down like this [motions pulling basket straight down] like upside down on the way down it stays in until it gets to the bottom and then it comes out.

Teacher: So you're using now this example of something that you've done at home where you have an object in a bucket – or a basket, you said – and what do you do? You –

Miranda: I go like this and then I pull it down and it stays at the top until I stop and then it comes out. [Motions swinging overhead and pulling down, lifts hands to show that it stays at the top of the basket.]

Teacher: So you swing this – what's in the basket? What object is in the basket?

Miranda: Sometimes I put like, like a little toy cat that I'm playing roller-coaster with and put it in there and I pull it down and it stays in the back [motions that the cat is up at the top] until I stop and then it comes out.

Wholly aside from the fact that this analogy leads to the correct prediction, this analogy shows the beginnings of deep scientific reasoning. As I will show in later chapters, mechanistic analogies to phenomena with which you have experience are ubiquitous in the scientific literature. Furthermore, once this analogy is brought up the tone of the conversation changed; student hands shot up, and mechanistic reasoning and scientific explanations were brought up. In an attempt to understand this moment – what, exactly, was the significance of Miranda's analogy, what are the assertions that it makes, the cognitive work that it does, why it was brought up, how it was negotiated, how the other students react to and negotiate the analogy – there are few models of analogical reasoning to turn to, fewer still on spontaneously-generated analogies; studies on analogical reasoning suggest that comments like Miranda's should be rare, are indicative of expertise, and more likely with prompting by the teacher. Furthermore, most models of analogy are stem from variable process/regularity approaches to explanation and not causal or meaning-based models. In this chapter I will outline previous studies on analogical reasoning, their philosophical assumptions, the strengths of these approaches and their shortcomings. I then outline the tradition in which my own study is based and explain the theoretical nature of this dissertation and its methodology.

History of Research on Analogies

Past research

Owing, perhaps, to the behaviorist tradition in psychology, the success of experimental methods in more objective sciences, or stemming from the more recent analogy of the mind to a computer with its fixed rules and stability, studies in learning, particularly in cognitive science, have tended to focus on quantitative studies in laboratory settings. The history of analogical reasoning is no exception.

The most well known example of experiments on analogical reasoning is that by Gick and Holyoak (1980 p 307-308). In their study, participants were presented with Duncker's (1945) "radiation problem." The problem begins with an anecdote:

> A general wishes to capture a fortress located in the center of a country. There are many roads radiating outward from the fortress. All have been mined so that while small groups of men can pass over the roads safely, a large force will detonate the mines. A full-scale direct attack is therefore impossible. The general's solution is to divide his army into small groups, send each group to the head of a different road, and have the groups converge simultaneously on the fortress.

The students were told to memorize the above passage and then asked to solve the following problem:

> You are a doctor faced with a patient who has a malignant tumor in his stomach. It is impossible to operate on the patient, but unless the tumor is destroyed the patient will die. There is a kind of ray that may be used to destroy the tumor. If the rays reach the tumor all at once and with sufficiently high intensity, the tumor will be destroyed, but surrounding tissue may be damaged as well. At lower intensities the rays are harmless to healthy tissue, but they will not affect the tumor either. What type of procedure might be used to destroy the tumor with the rays, and at the same time avoid destroying the healthy tissue?

Few students were able to solve the problem without explicit instruction to use the story that they had memorized. Once prompted, over 90% of students could solve the problem correctly using the convergence principles from the fortress story. This study has been widely cited as evidence that students find analogical reasoning difficult and that transfer is a rare phenomenon. Furthermore, it established a paradigm for investigating analogical reasoning: present participants in the study with two analogically similar scenarios and see if they notice/draw the intended analogy.

This methodology has been reiterated in future studies of analogical reasoning with similar results. In one study, Gentner, Ratterman and Forbus (1993) gave subjects a series of stories to read and followed up one week later with another set of stories. Some stories were structurally similar to stories in the first set, while others shared superficial features – about a similar topic or involving a similar kind of animal, say. The subjects were then asked which of the original stories these reminded them of and they chose the stories that shared superficial features. Again, the authors argued that subjects are not drawing analogies between deep structural similarities. However, Markman and Gentner (1993) report a study in which they ask participants to look at two pictures and find the "same thing" in the two photos; they found in this case that items that occupied similar *roles* were more often chosen as similar than superficially similar items.

Novick (1988) reports a similar finding in the context of mathematics to Markman and Gentner's findings – that analogies based on structure are possible – but that such analogies are more likely if the participant has sufficient expertise in the subject. (Which echoes findings by Chi, Feltovich and Glaser (1981) in which expert physicists tend to group problems based on principles rather than surface similarities, while novice physics students grouped the same problems using superficial characteristics.)

These studies, and those with similar methodologies, are powerful for their clear findings; they tell us quite definitively that in these scenarios, under these circumstances, subjects behave in this way. Indeed, this methodology, in the tradition of scientific based reasoning (SBR), is hailed in a National Research Council report, *Scientific Research in Education* (2002).

Limitations of past methodology

What, then, are the limitations of such research for understanding spontaneously generated analogies in science? While it has its strengths of clear and exact findings, I claim that such focused, constrained, laboratory-based studies (1) establish too strong constraints on what counts as analogical reasoning, (2) strip analogies of the crucial context in which they are constructed, and (3) fail to capture a causal explanation of analogical reasoning. I detail these below, and then introduce a qualitative alternative to such studies of analogical reasoning. I conclude by introducing the methodology employed in this thesis.

(1) Constraints

Consider the story by Hammer et al.'s (Hammer, Elby, Scherr, Redish, 2004) of a student discussing the size of mirror necessary to see your entire body in it. This student, Sherry, determines that

> you need a mirror the same size as your body, because your whole body has to be able to fit in it. Other students in her group used ideas about reflection to argue that the mirror would need to be half that size, but Sherry defended her reasoning. The next week she told her group about a discovery at home: She owns a mirror roughly half her height, and it shows a reflection of her whole body. She had known the answer to the question all along – she saw it every day.

In their article, this anecdote is brought up to call into question the notion of transfer. I mention it here to suggest that even when students are not drawing appropriate analogies – such as between the tumor and the fortress in Gick and Holyoak's– they may be drawing deep analogies nonetheless. Sherry, the authors suggest, may have been drawing a tacit analogy to doors or paintings instead of the more correct analogy to windows. The participants in Gick and Holyoak's study may be drawing analogies to bullets, sound in rooms, or light coming in through windows (it certainly seems just as bright by the window as it does in the center of the room). Gick and Holyoak may claim that participants did not draw the desired analogy between the tumor and the fortress, but they may not claim that students did not draw an analogy.

(2) Lack of context

Similarly, Gentner, Ratterman and Forbus's findings demonstrate that similarity – or, more accurately, reminding – is based initially on superficial characteristics when done in the context of a laboratory, but these stories lacked context and immediacy. Recently I was explaining to a friend the story of *Moneyball* (Lewis, 2003), in which a baseball manager ignores baseball's cultural wisdom of choosing draft picks in favor of statistical analysis by Harvard graduates. My friend replied that he was reading a similar story about Björk in the New Yorker (Ross, 2004) and commented that this seems to be a trend in nonfiction writing – to tell the story of someone who has an entirely different perspective on the "system" and revolutionizes it despite naysayers to great success. In this real-life context, comparing *Moneyball* to superficially similar stories (say, "Casey at the Bat," Thayer, 1997) would have been unnatural and bizarre, while comparing *Moneyball* to Björk was creative and insightful, but also natural and a logical conversational step. In a laboratory setting, with few stories to choose from and no reason for the stories to be told in the first place, our cognitive behavior can be unnatural and bizarre. It is important, then, to pair our laboratory based studies of cognition with studies "in the wild."

Why has it required conscious and deliberate effort to integrate context into studies of learning and cognition? As Lemke explains:

> We blame the early Moderns of Rene Descartes' 17th-century Europe for cleaving Mind from Body and Society from Nature (e.g. Shapin & Schaffer 1985, Latour 1993). From them we inherited a chain – cognition in the mind, mind "in" a material brain, brain in a mindless body, body in a natural environment separate from society, society made up of persons not bodies, persons defined by cultures, cultures created by minds – a chain that binds us still and runs us 'round and 'round in ever smaller circles.
>
> We rebel, we transgress. We want the freedom to construct a materiality of mind, an intelligence of the body. We want meaning to arise from material processes and Culture to be once again a part of Nature. We want to re-situate cognition in a larger meaning-making system of which our bodies and brains are only one part. We are willing to pay the price, to abdicate our Lordship over Creation, to become partners rather than over-seers. Creation, after all, has been getting pretty unruly anyway.

That is, Cartesian dualism, which proved so powerful for the traditionally "hard" sciences, has left its legacy in the behavioral sciences which may not be appropriate: it places *meaning* outside the scope of scientific research, separating questions of meaning – which are intimately tied to context – from questions of science.

Since the initial studies of analogy reported above, which occurred in the early 1980's, researchers in cognitive science and education have become increasingly concerned with the assumptions noted by Lemke that laboratory-based studies make on the nature of cognition. Gibson (1979), studying perception, emphasized the need to study vision in terms of people behaving in the real world performing meaningful tasks rather than subjects responding to the artificial and acontextual conditions of the laboratory. Lave, continuing this paradigm into the learning sciences, performed a series of classic studies (Lave 1988, Lave & Wenger 1991) observing people – tailors, midwives, and dieters – in real-world settings as they engaged in problem-solving. She found that their strategies in these immediate, concrete, specific, and meaning-rich situations differed from the disconnected problems of school or the tasks posed in a psychology lab. From these studies, she coined the term "situated cognition" to describe cognition as a "nexus of relations between the mind at work and the world in which it works" (Lave, 1988 p. 1), and any claims about how cognition "works" must take into account the world in which it is working.

(3) Causal explanation

A final concern for laboratory-based studies of analogical reasoning comes from Maxwell's (2004) concerns about the types of claims these studies can make about causation. That is to say, he finds fault with what causation *means* when arrived at from a laboratory-based, quantitative study. Concerned with the emphasis on scientific based research (SBR) in the National Research Council's *Scientific Research in Education* (2002) report, Maxwell traces the philosophical traditions of SBR and argues that it assumes a "regularity" view of causation. The regularity view is

> based on an analysis of the contribution of differences in values of particular variables to differences in other variables. The comparison of conditions or groups in which the presumed causal factor takes different values, while other factors are held constant or statistically controlled, is central to this approach to causation.

He further argues that "the central manifestation of the regularity view in the NRC (2002) report is its presentation of causality as primarily pertaining to *whether* x caused y, rather than *how* it did so" (Maxwell, 2004 pp. 125–129). This claim is certainly true in the studies of analogical reasoning reported above: these experiments cite circumstances under which deep analogies are or are not drawn (such as: expertise is important, deep analogies are rare in the context of comparing two items), but make no claims as to why analogies are drawn, what cognitive work these analogies do, the purpose that analogies serve and why students fail to draw analogies in certain situations.

These three concerns – the constraints that laboratory based research places on analogical reasoning, the claims of situated cognition that demand ecologically valid research, and failure of variance theory research to arrive at meaning or mechanism – have motivated researchers to perform qualitative studies of analogical reasoning. These studies are discussed below.

Recent approaches to the study of analogical reasoning

Noting the criticisms of laboratory-based research on cognitive processes that claim "what we know of cognition is based on arbitrary tasks bearing little relationship to the cognitive processes that occur in naturalistic settings" (Dunbar and Blanchette, p 334), and in the tradition of situated cognition research methodology, Kevin Dunbar and Isabelle Blanchette investigated the use of analogy in natural contexts. They explain, "we wanted to discover what similarities people note and under what circumstances their reasoning is based on superficial or structural similarities." They began by video- and audio-taping molecular biology and immunology labs and analyzing the types and frequency of analogy generation in these conversations.

A similar approach was taken in a study of generated analogies in 6th grade mathematics classrooms. A recent article by Richland, Holyoak and Stigler (2004) reports an in-vivo study of analogies with their research in eighth grade mathematics classrooms. As with Dunbar's methodology, Richland *et al.* construct a coding scheme and deep analysis of the kinds of analogies that are generated in the classroom.

The analyses performed on the data from these studies, though situated in a naturalistic context and with strong qualitative components, also continue a quantitative paradigm. These and other studies (for example, Pittman, 1999 and VanLehn, 1998) look at the kinds of analogies, the frequency of these analogies, rely on a large corpus of data to draw statistical claims about *what* happened – again "primarily pertaining to *whether* x caused y, rather than *how* it did so" (Maxwell 2004) or, perhaps more accurately in these cases, *if* x occurred and not *why*. To get at the *meaning* behind analogical reasoning – that is, what are the assertions that analogies make, what cognitive work do they do, how might the mind be organized to allow for this – I rely not on statistical analyses of data or rigorous coding of transcripts (which, of course, are invaluable tools of the educational researcher and a crucial component of many important methodologies), but instead a variety of approaches (primarily phenomenology and case study) and on the philosophy of causality behind process theory.

An alternative to the regularity view (which Maxwell notes as characteristic of variance theory) is that of "process theory" (Maxwell, 2004):

> Process theory… deals with events and the processes that connect them; it is based on an analysis of the causal processes by which some events influence others. It is fundamentally different from variance theory as a way of thinking about scientific explanation… (p. 5)
>
> A realist, process-oriented approach to explanation is compatible with, and facilitates, the key strengths of qualitative research. In particular, it recognizes the reality and importance of *meaning*, as well as of physical and behavioral phenomena, as having explanatory significance, and the essentially *interpretive* nature of our understanding of the former. It also recognizes the explanatory importance of the *context* of the phenomena studied, and does so in a way that

> does not simply reduce this context to a set of "extraneous variables." It relies fundamentally on an understanding of the *processes* by which an event or situation occurs, rather than simply a comparison of situations involving the presence and absence of the presumed cause. Finally, it legitimates a concern with understanding *particular* situations and events, rather than addressing only general patterns. (p. 8)

Maxwell then argues that qualitative research methods, because of their strengths at "identifying causality in particular cases, the importance of context as integral to causal processes, and the role of meaning and interpretive understanding in causal explanation" are a crucial element in education research.

It is in this tradition and due to these concerns that I choose to approach understanding student-generated analogies as they occur in classroom discussions.

Methodology

This thesis is a theoretical account of generated analogies in science, which began with an insight into Miranda's generated analogy above; namely that the thing she seems to be making an assertion of *categorization* rather than a direct one-to-one mapping of this cup to that experience of twirling her basket. Following this insight, I developed an account of generated analogies as assertions of categorization using the events in this classroom research from categorization. This account was then compared with generated analogies in other contexts: different classrooms of various ages, historical accounts of analogy use in science, research group meetings and informal conversations. In these analyses, I compared my story of categorization to the existing accounts of analogy (primarily structure mapping), and I will argue that a categorization perspective is more successful and generative than the others. Further implications of this perspective may then be tested in a more quantitative methodology.

A note on the data

None of the data presented in this thesis was collected for the purpose of studying analogies in science. While collecting data for a project on student inquiry in physical science, and knowing that I was interested in studying analogies in science (because of my own propensity for them), Miranda's particularly powerful student-generated analogy struck me. At the same time, I was reading a book by Lakoff (1987) – *Women, Fire and Dangerous Things: What Categories Reveal About the Mind.* With this one example of student-generated analogies and this one perspective on cognition, I began to develop a rough theoretical perspective for understanding student-generated analogies in science as assertions of categorization around this first analogy. I then turned to a corpus of data from student inquiry into physical science, research group meetings and classrooms to check against my account of analogical reasoning.

The case study methodology

Such a study is indicative of the case study tradition. The case study primarily addresses the *how* and the *why* research questions – in my case, why analogies are generated, how they help students and the cognitive work that they do. The case study aims to provide a detailed description and analysis of the observed case. It acknowledges the importance of studying the phenomenon as a whole and does not consist of a linear model of inquiry, noting that "there are complex relationships within phenomena, [and] taking them apart may result in losing some of their important aspects." Additionally, the "case study is also *naturalistic* in the sense that it studies cases in their physical context, in which the researcher is also interested… the researcher has limited or in some cases no control over the case of study. Case study method also requires the study of a contemporary phenomenon or situation within its real life context" (Louca, 2004, p. 35).

Furthermore it is the evaluation of a single case that Maxwell (2004) and Davidson (1967) argue may be a more powerful method for arriving at causality than the variant theory approaches. Davidson notes that we "can infer cause in single experiments . . . [and that] providing them with conceptual help in doing so is a virtue, not a vice; failing to do so is a major flaw in a theory of cause-probing methods" (Davidson, 1967, p. 465).

One key component of the case study, indeed of all qualitative research, is triangulation of information in which "researchers make use of multiple and different sources, methods, investigators and theories to provide corroborating evidence. Typically this process involves corroborating evidence from different sources to shed light on a theme or perspective" (Creswell p 202). As I continued taping student conversations in physical science, which were replete with spontaneously generated analogies, I had further data to bring into and try out against my theoretical framework. This data primarily comes from elementary school classrooms throughout Maryland, ranging from second through sixth grade. The teachers in this study were part of the project *Case Studies in Elementary Science* and are particularly skilled at listening and attending to student ideas in science, which was significant in providing me with student-generated analogies. In addition, I used data from studies on high school and undergraduate physics students – data initially acquired for other research purposes – along with tapes from research group meetings and faculty conversations. And finally, the framework was compared to analogies by scientists, as reported in studies from the history and philosophy of science, comparative literature and popular non-fiction. The analysis began with a phenomenological analysis, which will be explained in the following chapter and then a more ontological, causal analysis, which I will describe in Chapter 5.

Summary

This is a theoretical dissertation, one that argues for a particular perspective on student-generated analogies and the ontology of mind. As such, quantitative methods – even those that are typically used in more qualitative research (coding, for example) – are not employed here. That is not to say that these are not relevant to a framework of spontaneously-generated analogies. However, as Maxwell (2004) argues,

> I would argue that strictly experimental designs, with no qualitative components, are a comparatively powerful method for understanding only when three conditions obtain. First, there should be a well-developed theory that informs the intervention and research design and allows interpretation of the experimental results (Bernard, 2000, pp. 55–56)… Second, the causal process investigated should be manipulable, fairly straightforward and simple… Third, the situation should not be conducive to the direct investigation of causal processes.

This thesis aims to begin with the first of these criteria by understanding the *why* of student-generated analogies, providing a framework of categorization and consistent with a manifold ontology of mind. Once established, the ability to manipulate the causal processes and whether or not these may be investigated directly may then be asked.

Chapter 4: Phenomenological Coherence

Introduction

The central thesis of this dissertation is that student generated analogies in science can best be interpreted as assertions of categorization. This description of analogy began with an analysis of a single classroom, first introduced in the previous chapter. In this chapter, I will highlight particular *phenomenological* aspects of this and other analogies and the negotiation of these analogies. I will explore the consistency of these aspects with a categorization framework. Alternative theories of analogical reasoning will be contrasted with a categorization description. In following chapter, I will address the implications that these phenomenological properties have on cognitive structure and how a theory of cognitive structure that consists of a manifold ontology of mind can, in turn, provide a more formal definition of analogy and account for the phenomenology described here. The phenomenological features that will be detailed below are: multiple analogies that serve to enumerate a category, multiple analogies that serve to analogy "hop," far-transfer analogies introduced before near-transfer analogies, constructing the base of an analogy rather than recalling the base from memory, a variable representation of that base, and analogies as offering an *alternative* to another way of understanding this phenomenon.

Models of analogy from the literature

To understand these phenomenological aspects of generated analogies, one might first turn to an established model of analogy. As noted in Chapter 2, these models, first developed in the 1970's, have evolved to the commonly accepted models of structure-mapping (Gentner, 1983) and MAC/FAC (Gentner and Forbus, 1991). The initial theories of analogy, commonly referred to as feature-matching theories, were based on similarities between features, properties and behaviors of the primary and secondary subjects of the analogy (Johnson and Malgady, 1980, Miller 1979, and Tversky 1977). It has since been widely recognized that the claim of "similarity" is vague and underdetermines the correspondences and nature of analogical reasoning (Lakoff 1987). Similar claims were made in categorization: while members of a category were assumed to have certain features in common, defining these features was problematic. Some features, such as "seat" for the category of objects called "chairs" appear to have names that showed them not to be meaningful prior to the knowledge of the object as a chair. "Large" for the object "piano" has meaning only in relation to categorization of the object in terms of a superordinate category. And "you eat on it" for the object "table" is a functional attribute that requires knowledge about humans, their activities and the world (Rosch 1978). Similarly, analogies are not based on superficial attributes and feature-matching between subjects, but apply to a more abstract structure of the subjects. Gentner (1983) developed a theory, structure-mapping, to address the fact that analogies are not feature comparisons, but much more structural.

Structure-mapping theory argues that interpreting an analogy involves both alignment and projection. The process is described in Bowdle and Gentner (1999):

> Structure-mapping theory assumes that interpreting a metaphor involves two interrelated mechanisms: alignment and projection. The alignments process operates in a local-to-global fashion to create a maximal structurally consistent match between two representations that observes one-to-one mapping and parallel connectivity (Falkenhainer, Forbus and Gentner, 1989). That is, each object of

> one representation can be placed in correspondence with at most one object of the other representation, and arguments of aligned relations are themselves aligned. A further constraint on the alignment process is *systematicity*: Alignments that form deeply interconnected structures, in which higher-order relations constrain lower-order relations, are preferred over less systematic sets of commonalities. Once a structurally consistent match between the target and base domains has been found, further predicates from the base that are connected to the common system can be projected to the target as *candidate inferences.*

There are several shortcomings of structure-mapping theory when trying to understand student-generated analogies. First, such a model is designed to explain "interpreting an analogy" and not the process by which that analogy was created.[1] Additionally, while structure-mapping can illustrate *what* an analogy is, it is not clear *why* a student would map knowledge from one domain onto another, under what circumstances analogies are generated, or how the analogy will evolve in the classroom. Structure-mapping is a powerful model for how an analogy, once introduced and understood may be formalized and used to draw further inferences, but it is not a model for how analogies are generated and the kind of work this generation does.

Analogies as categorization

To address the phenomena mentioned above and understand the role of generated analogies, I will argue for a categorization framework; that is, I assert that the role of Miranda's analogy between a falling cup of water and a toy cat swinging in a basket (first mentioned in chapter 3 and explored in detail below) is not to establish a one-to-one mapping between this particular cup of water and a particular instance of swinging a

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[1] In some references, structure-mapping is portrayed not as a model for how we interpret analogy, but generate (Falkenhainer, Forbus and Gentner, 1989 p 2): "Structure-mapping decomposes analogical processing into three stages…: 1. Access: Given a current target situation~retrieve from long-term memory another description, the base, which is analogous or similar to the target."

basket overhead. Rather, the cat/basket serves to represent a more abstracted, general category – that of, perhaps, containers that do not spill their contents when overturned (though certainly not so well-defined in Miranda's mind, and lacking the propositional structure that such a characterization implies). By constructing this category, she has introduced an alternative cognitive model, allowing for a new set of causal mechanisms to be explored. As this category is negotiated, adapted and understood, additional analogies are introduced as a means of negotiating and understanding this category. This idea echoes and expands upon claims made in cognitive science regarding the interpretation of metaphor. When the base of an analogy (termed the vehicle in the context of metaphor) is used as both an exemplar and as an ad hoc name for a category, Glucksberg et al. (1997) call this linguistic move "dual reference." As an example of dual reference, the phrase "a responsibility is a shackle" can be used to refer to the concrete,

> physical device that is made of metal, often has chains, can be locked around someone's arms and legs, and so forth, and it can also be used to refer to the abstract, general category of constraining entities. We refer to such abstract, general concepts as attributive categories. (Glucksberg et al 1997 p 334)

The authors claim that "nouns can be used to make dual reference whenever a superordinate category has not been lexicalized and a category exemplar is available that is prototypical of that category." I will expand upon this idea to include more than nouns in metaphorical scenarios and focusing on the generation of analogies

Again, in this chapter I will focus on the phenomenological aspects of generated analogies in science – in particular, the pattern of multiple analogies, chains of analogies, near and far transfer analogies, analogy bases constructed as opposed to recalled, and the variability of representation of the base in such analogies. In the following chapter I will focus on the underlying cognitive structure, cognitive models and ontology of mind that is consistent with this analysis.

Multiple Analogies

The first phenomenological aspect of student-generated analogies that I present is that of multiple analogies. In each of the following transcripts, an analogy is generated and then, in the negotiation of that analogy, further analogies are brought up. None of the following analogies is at odds with the initial analogy, nor are they extensions or modifications of that analogy, rather they are consistent with the initial analogy and, I argue, serve to aid in understanding the category – the *kind* of thing – that the initial analogy asserts. Below I present these multiple analogies and demonstrate the consistency between multiple analogies and a categorization framework of student-generated analogies in science. This chapter consists primarily of kind of checklist of phenomena that student-generated analogies have in common with categorization; in the following chapter I will account for this correlation in a more theoretical manner by addressing a theory of mind that can account for and explain these phenomena.

Multiple analogies: Example 1

In Chapter 3, I first introduced the following analogy from a 5th grade classroom in a rural Maryland public school. In this transcript, the students have been visited by the science resource teacher and posed the following question (NASA, 1999): a cup full of water is inverted on a cookie tray and the tray is rapidly pulled out from underneath the cup (see Fig. 4.1). What happens to the cup-water system? The students will later observe

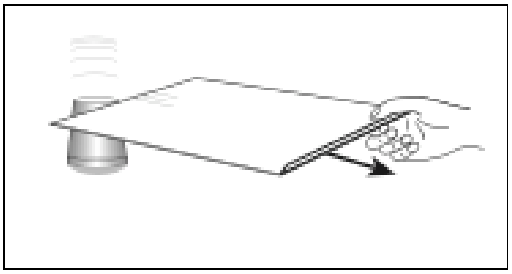

Fig. 4.1: The Experiment: A tray pulled out from under a cup

that the water does not leave the cup as it falls to the ground – the cup falls at the same rate as the water and the water will only spill out once it reaches the ground. However, perhaps not surprisingly, the students initially predict that the water will spill from the cup or spread across the tray. A student then offers a different prediction and introduces the analogy (transcript 2, lines 8 – 36) that the cup of water is like a cat in a basket and will not spill when overturned

The claim that I will continue to make throughout this dissertation is that Miranda, with her analogy, is making the assertion that the cup of water belongs to a category or class of phenomena that is typified by the toy cat swinging in the basket, rather than mapping the structure of swinging a cat in a basket to the phenomenon of the overturned cup of water. Consistent with this story are the multiple analogies that ensue. Following Miranda's introduction of the analogy to a toy cat swinging in a basket, the following analogies are introduced, consistent with Miranda's analogy: throwing buckets of water (transcript 2, lines 134 - 144)

Teacher:	It could turn sideways like that. And that would make a difference. Okay let's get – a lot of you have been very patient. Cody?
Cody:	Um because when I was um having bucket full of water and I swing it around and then when I throw it the bucket of water still stays in there- the water, and… Yeah and then when I throw it the bucket of water still stays until it hits something.

throwing a bag of Halloween candy (transcript 2, lines 179 – 189) and tossing dice in a hat,

> Isaac: Um I pre- I don't- um I agree with Miranda but I don't think air has anything to do with it. Because um yesterday at Trick-at-Treat I had like a bunch of candy and I swung it around that's like when I was bored and stuff –
>
> Teacher: In your bag?
>
> Isaac: Yeah. And none of the candy came out. I like kept on swinging it and also when me and Johnny play monopoly there's like this little hat that we play with when we roll the dice [Teacher: Mmm hmm.] and like we always put the dice in and flip it back to each other with the dice in it and we always catch it and it stays and the dice stay in.

and twirling Easter candy (transcript 2, lines 200 – 207)

> Teacher: …Alexandra?
>
> Alexandra: Um when Miranda said how when she dropped the cat in a um basket- I've done that with um my Easter candy but with more candy in it and when I turned it over when I got up here and it dropped it all went everywhere.
>
> Teacher: But when you were swinging it, it didn't fall out until you got up here and then stopped and then it all fell out. [Alexandra nods.]

In the structure-mapping model of analogy, the role of multiple analogies is not clear: if students understand the target and base and their relationship to one another, the analogy has served its purpose and reiterations of this structure-mapping with additional analogies should not be necessary. However, multiple analogies are consistent with categorization, as categories typically consist of multiple members and these serve to better define and negotiate the category they are constructing. Researchers have shown, perhaps not surprisingly, that students' abilities to categorize properly are greatly enhanced when multiple members of a category are shown (Namy and Gentner, 1999) and these multiple analogies can be understood to be negotiations of the category Miranda is asserting.

What is surprising about these multiple analogies is that, although they are consistent with Miranda's cat/basket analogy, they are not always introduced by students who agree with Miranda's prediction: neither Cody, who introduced the bucket of water analogy, nor Alexandra, who brought up the Easter candy analogy, believe that the water will stay in the cup, and Isaac agrees with Miranda's prediction but, without a rationale for why, disagrees with the suggested mechanism of this prediction. These students are not discussing the "mapping" of a base onto a target: they are not relating their analogies to the cup of water, they have not put items in a one-to-one alignment or made candidate inferences, as structure-mapping suggests. Rather they are exploring the phenomenon of the toy cat in the basket in its own right by mentioning other members of the category that it represents – that is, other items that do not spill from their containers – as a means of negotiating the category to which the base of the analogy belongs.

A particularly telling moment in the multiple analogies as categorization story is when Alexandra claims (transcript 2, lines 200 – 207):

Alexandra:	Um when Miranda said how when she dropped the cat in a um basket- I've done that with um my Easter candy but with more candy in it and when I turned it over when I got up here and it dropped it all went everywhere.
Teacher:	But when you were swinging it, it didn't fall out until you got up here and then stopped and then it all fell out. [Alexandra nods.]

What does Alexandra mean when she claims to have "done that?" What is *that*? No one ever explicitly discusses the abstracted "category" of "overturned containers that do not spill their contents"– and yet *that* cannot refer to the concrete example that Miranda mentioned: Alexandra does not claim to have spun a basket overhead. Instead, Alexandra, indeed the whole class, recognizes that Miranda is using the toy cat in a basket as an instance of a more general category, one that Alexandra represents with her Easter candy and refers to by her claim to have done "that." In another use of "that" to refer to the class of phenomena that her initial analogy constructs, Miranda, in line 55 (transcript 2), says:

> Miranda: And it'll be the same thing with the water the air will push the water up until it falls down and then it will go everywhere. Because when it comes down the air is pushing upwards and [it keeps/I keep?] the water in there- because I've also done that in the bathtub when you've got your cup, I'll like I'll fill it with water put my hand and drop it the water stays in until it hits the bathtub and then it goes everywhere.

To claim "I have also done that" signifies there is a "that" to refer to – the category of phenomena to which the cat/basket, cup/water and Easter candy/basket belong. The use of "that" is often indicative of categorization: imagine that you are telling someone about training for and running a marathon and she replies "I've done that." One would assume she means she has run *a* marathon – not the same marathon as you, but rather recognizes the (slightly) more abstract category of marathons in general. For a more abstract case, consider the example from the previous chapter, in which a friend and I were discussing *Moneyball* (a story about baseball management) and he mentions that he is reading a similar story and brings up Björk (an Icelandic pop star). Though I don't have a transcript of our conversation, one can imagine saying, "That's a really popular story to tell these days." In this case, "that" would mean an abstracted type of story – a category to which *Moneyball* and Björk belong. Miranda's analogy, then, is to instantiate this category of containers that do not spill when overturned – construct it as a category and assert that the cup of water is a member. The other students understand this, come up with other members of the category that Miranda has constructed, and debate whether or not the cup of water is, indeed, a member of this category and Alexandra's comment to say that she has "done that with um my Easter candy."

If the use of the word "that" seems scant evidence for categorization to be at play, this is only due to the fact that categorization is so ubiquitous it frequently escapes our notice. Every conceivable noun describes a category, and every time I identify a window as being, in fact, a window, I am making a categorical assertion. Verbs, too, can be seen as categories; the claim "I leap" makes a categorical assertion about the *kind of* activity I am doing, ignores the subtle differences between *this* leap and *other* acts of leaping – just as running-a-marathon or swinging-something-overhead-so-that-its-contents-do-not-immediately-fall-out can be a category. While running-a-marathon is a relatively exact category (in this context), the nuances of many categories can be quite complex. Consider all of the ways in which "leap" can be used: "a leap of faith," "look before you leap," a "flying leap," or "leap frog." Or, as Hofstadter (2004, p. 505) explains,

> such lists go on and on virtually forever, and yet the amazing fact is that few people have any inkling of the vastness of their mental lexicons (see Becker 1975). To be sure, most adults use their vast mental lexicons with great virtuosity, but they have stunningly little explicit awareness of what they are doing.

And just as lexical items and phrases describe categories, there are categories for which we have no simple labels. As with the *Moneyball*/Björk analogies, there are "stories about someone who has an entirely different perspective on the 'system' and revolutionizes it despite naysayers to great success." And in these categories, multiple members serve to negotiate and define the category. As a second example of the role of multiple analogies as defining and negotiating a category, I present another transcript of student conversations of science.

Multiple analogies: Example 2

The following transcript, first introduced in Chapter 1, is from an undergraduate physics course for elementary education majors, Inquiry into Physical Science. The students have been investigating the electrical properties of Styrofoam and metal, and noticed that Styrofoam is easy to charge (simply rub with wool) and metal is not, but metal can easily give you a shock and there are ways to charge metal once you have a charged object. They have been asked to explain the differences between these two materials by describing "what life is like" for a charge in each. In doing so, multiple analogies are introduced. (In this transcript, by class convention, the two types of charges are referred to as "top" and "bottom.") Hana begins the discussion with an analogy between the charges and fish (Transcript 1, lines 1 – 17):

Hana: I kind of see the charge in metal as like, fish in a fish bowl? Like they never really stop moving, they're always kind of floating around wherever they kind of feel like going and that's just how I see it in my head, like them always moving around. And I don't know what hap- I don't know how to describe it really I don't really know what happens once another charge is brought closer then.
Instructor: Does this make sense to you then?
Hana: Yeah.
Instructor: So this is – so this is like two kinds of fish. [Hana: Yeah.] And in metal they can move around. They're kind of stuck inside the bowl, but within the bowl they can move around.
Hana: But I also think that they can leave the bowl at some point because –
Instructor: Well we get shocked right?

This idea of continual motion of the charges is mentioned in another analogy (Transcript 1, lines 20 – 33):

Kelli: That same idea I was thinking except more like ping pong balls that bounce all around and that's why if there's top and bottom charges they're moving around a lot and they're kind of attracting and repelling and attracting and repelling each other the tops and bottoms that go all over the place – but once the extra bottom charge is added it's almost trying to like reneutralize itself and the tops are attracting to the extra bottoms. And then they're trying to kick out the other extra bottoms so they can get back into their whole little [Student: Balance.] balance. Bouncing around.

Instructor: So this- I think what you're offering is an explanation of why I get a shock. Is that – am I wrong?

Kelli: No, you're not.

In both analogies, the students are, first, introducing an imagistic analogy that describes the motion of the charges and then, in the case of Kelli's analogy, explaining how, mechanistically, this is consistent with observed phenomena. However, a student notes the following (transcript 1, lines 46 – 52):

Christie: We were thinking that – like they were saying that in metal it's always moving, so if it's always moving it has more room to move and that would mean to say that the molecules are less tightly packed together or less dense and we were thinking of Styrofoam as more dense than – I'm just trying to figure out first if that's right and how it relates.

A second group of multiple analogies stems from Christie's comment, "If it's always moving it has more room to move and that would mean to say that the molecules are less tightly packed together or less dense and we were thinking of Styrofoam as more dense...". The students are all in agreement that charge seems to move more freely in metal than in Styrofoam (as in the analogies to fish in a fish bowl or ping pong balls bouncing all around), but this seems to imply that there is "more room to move" – meaning that metal should be less dense than Styrofoam. Lea, picking up on the fact that metal is more dense than Styrofoam, constructs an analogy that incorporates both: the Styrofoam is like cotton while the metal is like ice skating, in which the density of the medium allows for easy movement (transcript 1, lines 53 – 60). This category, media whose density allows for movement, is non-intuitive: crowds are hard to walk through, syrup is hard to walk through. In understanding and negotiating this category, other analogies are mentioned: a sponge, whose lack of density is a trap for water versus the dense countertop that allows water to flow easily (transcript 1, lines 61 – 66):

> Instructor: Lea I want to add – I think you're sort of what I when I hear you talk I'm thinking of like, pouring water into a sponge versus pouring water onto a hard surface. [Lea: Yeah.] Like this sponge is actually less dense and there's room for it to absorb the water and the you know if you pour it onto something hard there's no room for it to absorb.

And later another analogy, consistent with the previous two is mentioned – stepping stones that, when far apart, inhibit easy passage but when densely packed are easy to negotiate (transcript 1, lines 113 – 121).

> Lydia: I was going to say I think the pie plate is more dense but I do think that it's inside not outside because if there's more space to travel then the molecules can't get from one space to another easily but it's all real close together so it can sort of hop along inside.
>
> Instructor: Oh so it's like stepping stones [Lydia: Kind of.] like in the Styrofoam it's really far to the next stepping stone so it's like can't get there I'm stuck here. [Lydia: Right] but in the metal the stones are really close together so I can kind of walk across. [Lydia: Yeah.]

I will revisit this analogy in the following section for the manner in which it differs from those that came before. In the above transcript there are several analogies mentioned:

- charges are like fish in a fishbowl (lines 1-4)
- charges are like ping-pong balls (lines 20-24)
- metal is like ice-skating (lines 56-57)
- Styrofoam is like a sponge (line 63)
- charge flow is like steam escaping a shower (lines 98-104)
- metal is like a set of closely spaced stepping stones (line 120)

Some of these analogies are mentioned relatively independently, but, as in the case of Miranda's analogy and the multiple analogies around it, some analogies in the transcript above further develop a category that the original analogy has constructed.

Chains of Analogies

A second manner in which multiple analogies are used is not to flesh out a category, but as a means of "stepping" from one analogy to another. In this section, I will present examples of analogies that are not consistent with one another but can each be seen to be a slight "tweak" on the one that came before. Such analogies are consistent with findings from categorization – in particular family resemblance, described below.

It is important to note that research indicates categories do not have a fixed representation or set of criteria for membership. Our categories are constantly reshuffled and recast depending on the context. At times, the concept of leaping is very much related to movement, at other times to lack of support, and no dictionary definition can capture the full character of the way this word is used in everyday language. As noted in chapter two, "there is no one property that all games share, but rather there are family resemblances between games, so that "chess and Go both involve long term strategy… chess and poker both involve competition. Poker and old maid are both card games" (Lakoff, 1987 p. 16). Similarly, "leap-frog" and a "flying leap" indicate a kind of forward motion off of the ground, while a "flying leap" and "look before you leap" are situations in which you lack support. This family resemblance is indicative of two things: one, as mentioned above, that no one characteristic defines a category, and two, there is a hierarchy of categorization. Rosch referred to the most accessible level – the easiest to learn, recognize, recall, and shortest to name – the basic level and underlying this level are more fine grained categorizations: such as games dividing into card games.

If analogies, then, are assertions of categorization, we might expect multiple analogies as a way of negotiating the category, and chains of analogies (as with Go, chess, poker and old maid) as family resemblances are followed within a category, subdividing that category into a finer grained one. The analogies in the previous section are relatively consistent with one another as a particular category becomes increasingly defined. In this section, I present analogies that follow chains of "family resemblance" to tease apart distinctions and more narrowly define a particular categorization.

Chains of analogies: Example 1

The first transcript below is from a research group meeting of the Physics Education Research Group. Paul, a graduate student, is interested in authentic classroom activities and is discussing his definition of authentic. Key to this definition is that authenticity is a property not only of the activity but also but also in the way that the students relate to that activity and the coherence of this to the scientific community of practice (that is, do the students know what they're doing? Would scientists agree?). This is at odds with definitions of 'authentic" activities that situate authenticity as a property of the curriculum itself. In this transcript, analogies to authenticity are suggested, and multiple analogies are pursued. These analogies are both along the lines of honing in on and refining a particular analogy (akin to the multiple analogies above) and "family resemblance" analogies that are more "horizontal" than "vertical" chains. The transcript begins with David recapping Paul's concerns with the standard definition of authentic curricula, and Rachel's introduction of an analogy between "authentic" and "fun" (transcript 3, lines 1 – 9):

David: It's not a responsive definition of authentic. Authentic is defined pre-experience. And so what your [Paul's] sense is what's going to be authentic is about watching the student and and what is authentic for this group – may be different from what's authentic science for *this* group. And you don't like defining authenticity in a way that isn't responsive. So the content isn't responsive but also the sense of what is authentic isn't responsive.
Rachel: So ontologically authenticity is like fun. Which would be –
David: Oh that's great.
Andy: Oh that is beautiful!

The analogy is understood by the group and further explained in lines 17 – 29 (transcript 3):

Andy: – it emerges from an activity but it's really ultimately lives inside –
Rachel: Right and I mean you could say – I mean you couldn't look at a thing on paper and declare that it was fun until you could see people do it and see them have fun.
David: And it may be fun for some people and not fun for other people.
Andy: You could – an experienced teacher could make guesses about what's more likely to result in fun blah blah blah.
Rachel: Sure, sure. But really ultimately you don't know until after [inaudible]…
David: Or anyone – what what my kids think of as fun might not be the same as what Rachel thinks of as fun [trails off].

However, a weakness of the analogy is identified: Paul has argued that authenticity must not only be recognized by the students' relationship to the curriculum, but a (hypothetical) community of practice must have a similar understanding of the relationship between the students and this curriculum. This weakness is identified and alternative analogies are proposed (transcript 3, lines 38 – 70):

Leslie: Is there a community of fun practice? [Laughter.]
Rachel: Or norms? [Laughter.]
Leslie: Like with the community of practice the scientist is someone who's outside deciding whether or not it was science but with fun

there isn't – so it's a negative analogy – but with a community – yeah there's no community of practice.

David: I don't know what you mean – there's no authentic community of practice?

Leslie: You only have to ask a person who's having fun if they're having fun. But this (definition of authenticity) implies that you have to ask the scientists whether they're doing science.

David: Ahhh – right. Gotcha.

Andy: Not only does it have to be meaningful it has to be meaningful in the right way – but – yeah I'm having fun but it's – you know – low-brow fun instead of highbrow fun. Guffaw guffaw! Gotcha. [Laughter.]

David: So can we patch that? Is there, is there another…

Rachel: Good clean fun?...

Leslie: I have a multiple analogy if that's okay? I'm thinking it's more like worship – like, you know if you're worshipping but a religion is going to also decide if what you did was worship.

Andy: Oooh.

David: Right. Right that's good.

Andy: It's gotta pass both tests. That is good. Good clean fun works, too. You decide if it's fun, *I* decide if it's good and clean! [Laughter.]

Leslie: Or pornography?

The analogies above construct a particular ontology (as Rachel identifies) – or category – of adjectives: those that are not inherent properties of the object they describe, but, like "fun," are a measure of both the activity and the participant. This does not quite describe the sense in which Paul is speaking of authenticity. In his description of an authentic activity, Paul also relies on the coherence of the students' understanding of the activity with the community of practice's understanding of that activity. To patch the analogy, two alternative analogies are suggested. One is a more "vertical" analogy: replacing fun with "good clean fun" (line 60). I say vertical because this is similar to looking at games and then honing in on "card games" because the category "games" is too vague and lacks the detail that "card games" has. An alternative "patch" is to move more "horizontally" –

as if moving from “games of chance” to “card games” as Leslie (I) does by suggesting “worship” or “pornography” as alternative analogies.

The multiple analogies presented above do not serve the same role as the multiple analogies presented in the previous section. Instead of serving to negotiate and understand the category that the analogy constructs, they alter this analogy – however they do so in a manner consistent with categorization. One possible “tweak” to a category is to further parse it – categories have hierarchies (as with “chair” which is a base level category – and “easy chair” or “desk chair” or “recliner,” which are subdivisions of this category). Taking the idea of “fun” into “good clean fun” is such a move. An alternative move is one of “family resemblance” in which categories are related to one another within a hierarchy (as with “easy chair” and “desk chair”) – it is this move that Leslie makes in moving from “fun” to “worship.”

Chains of analogies: Example 2

Furthermore, these analogies, unlike the multiple analogies that are consonant with the cat in the basket, are in response to something problematic – a small piece of the story doesn’t work out. This is the story in the final analogy presented in the analogies regarding charges in metal (transcript I, lines 113 – 121) in which the metal is like closely-spaced stepping stones. Implicit in the analogies that the other students have suggested is that the charge will then travel on the outside of the metal: ice-skaters travel on top of ice and water travels on countertops – implying charge will travel on the outside of metal. This is very much a structure-mapping story, in which the structure of the base makes implications for the target: items in the base and the target are placed in a one-to-one alignment and inferences are projected from that alignment. Charge traveling on the outside of the metal is an inference that structure-mapping can predict and explain. In this regard, structure-mapping tells a story that is an important piece of the work that analogies do in science classrooms and in science, and address a part of analogies that I do not: how they are used to draw inferences and establish a sense of mechanism. My claims are not regarding Lydia's interpretation and understanding of these implications, but how they in turn construct new analogies. This implication is one that Lydia challenges. (I note that) The "tweak" to the analogies is then suggested by the instructor, who moves from a countertop analogy to a stepping-stones analogy.

Chains of analogies: Example 3

The following transcript from a third grade classroom presents another example of this "family resemblance" property of multiple analogies. In this classroom, the teacher, Trisha Kagey, has asked the students: if you are running with a beanbag and want it to fall on an *X*, should you release it before, when, or after you reach the *X*? In the discussion that follows, several analogies are introduced, many of which are slight modifications of the one that preceded it. Below I present transcripts from the chain of analogies:

- the beanbag is like a baseball bat (line 59)
- it is like a leaf being dropped from a bus (line 74)
- it is like a rock being dropped from a bus or a bike (lines 36 and 76)
- the leaf is like a feather, and a rock is different (line 136)
- the rock is like a tree and yet made from the things that are different (188)

The first analogy is mentioned (in transcript 4, lines 35 – 46) after Adam argues for his prediction with Newton's Laws. I present it here for completeness: this analogy is not a part of the "chain" of analogies that ensue but the teacher's instructions and the student's analogy may play a role in the other students' expectations about what kind of knowledge to bring to bear on the question:

> Teacher: …but trying to just explain it to someone using your experiences – see if you can use it that way. Explain to – like you're explaining to a kindergartner. They're not going to be able to understand that law.
>
> Adam: Like um – if – like if something – if you're riding your bike, um – it's in motion. And you're going to keep going until you get stopped by like – um, a rock or something. And, and – or going uphill. And so if you're on a bike, and you get – you can get stopped by something else, like a rock or something.
>
> Teacher: So if we're thinking of your analogy to a bike, or your explanation with a bike, what's stopping it, and this is –
>
> Adam: Um, no. Well, in the situation of dropping the beanbag. Like, um, it's thing is the ground, and because the beanbag is running against the ground, um – it's getting slower. Because like the beanbag is um – getting – I don't know how to explain this.

Connor, in lines 55 – 62 (transcript 4), does not address Adam's prediction and explanation, but instead offers his own analogy:

> Connor: I would think the bean bag would – might fall behind where you want it to fall because when I put – when I played baseball – they always said don't throw the bat because it might hit the catcher and not one of the um person because we're using metal bats, and – so we drop it, you drop it and then you – . Well, when I drop it, it usually swings backwards; it wouldn't be behind the plate instead of the front of the plate.

Connor's analogy changes as he considers it further (transcript 4, lines 71 – 78):

> Teacher: Why do you think it fell behind?
>
> Connor: Well actually it didn't mostly. It got on the side or in front because – well because you're supposed to drop it because you don't need a bat while you're running the bases. Once you drop it, I'm just thinking also, what Adam is – well a bus – well if you were on a bus and you had uh, this little leaf that you found, and the window was open, and you drop it, it will go – it'll be going backwards.

It is interesting to note that the original analogy that Connor introduced should lead him to predict that the beanbag falls ahead of you when you drop it – and the analogy he then offers that is consistent with his prediction is a scenario that he has not likely done. This phenomenological aspect of analogies will be explored later in this chapter. In terms of the chain of analogies that is being constructed, Connor has moved from the very similar running-drop to dropping from a bus. In lines 83 – 94 (transcript 4), another student challenges Connor's analogy and he tweaks it further:

> Lauren: Because I think that's cause – you're talking about a leaf that's falling? That's because the – it's sort of – the bus is going back, so it's making like the air move. And the leaves are really, really light, so the reason they are going backward is because – . Um, well it's going so fast – a bus is like going so fast that it's probably making the air go that way. So that way the leaves are going that way.
> [Many talking in disagreement.]
>
> Connor: What if you did it with a rock? The same thing will probably happen with a rock. Because you are probably like a bus, that you make the air come – no one moves, don't you notice that um, objects like in cars or something – when you're going really fast on your bike that are – that um, you sometimes, [inaudible] and leaves your ankle on your back step and actually move.

The distinction between the "little leaf" and the rock are considered in lines 146 – 150 (transcript 4), and an analogy between the leaf and a feather are drawn:

> Kamran: But, if you – cause you know a feather is – it, it, it goes with the air just simply its a light. That's why – same with a leaf. A leaf is very light. And if you – a leaf falls [Inaudible.] goes to air. It doesn't go, 'leaf – boom.' It doesn't go like that.

And then (transcript 4, lines 188 - 190) the idea of the leaf is tweaked into considering the weightiness of a tree:

> Kamran: Yeah, because the weight pulls it right down. If a tree – it's heavy, and it's heavier than all the leaves it has, so the leaves will make it fly.

Through these analogies, we see the students following a chain of reasoning that begins with a particular phenomenon – that of the running drop – and steps through a series of family resemblances to arrive at two subcategories of the running drop phenomena. Kamran's comment (line 188) explores some confusion in the distinction in these categories, saying "the weight pulls it right down. If a tree – it's heavy, and it's heavier than all the leaves it has, so the leaves will make it fly – flies here. And the tree, it will just go down."

These two sections have demonstrated that a feature of student-generated analogies in science is multiple analogies. At times these analogies that come up in student conversations are independent of one another, but often they are related and this property is one that is neither predicted nor explained by current models of analogy. The predominant model of analogies – in particular analogies in science – is that of structure-mapping. This model is admittedly designed to explain analogies that have been constructed and the role that they then play. However, as shown above, it cannot account for multiple analogies. Categorization, which inherently involves multiple members and has been demonstrated to relate items not through any set of formal rules but rather through family resemblance, more coherently captures the manner in which spontaneously generated analogies in science are constructed and negotiated. In the following two sections, I will focus on the choice of the base for the analogies that students generate: first focusing on the base as a construction as opposed to a recollection, and then considering the role that similarity to the target of the analogy playas in the selection/construction of this base.

Construction of the base

Depiction of the base in research on analogies

Analogies are often depicted as a mapping from a well-understood base to a less-understood target, and implicit in this depiction is that the base is something that was previously known, experienced, considered, and then, during the act of the analogy, recalled. The following quotes (with italics added) about analogy reveal this assumption, in which the analog (or base) is "retrieved," "stored in memory," "accessed," and "in memory," but not "constructed" or "created":

- "A theory of analogical reasoning must explain how an analog is *retrieved*." (Vosniadu and Ortony, 1989 p 7)
- "Given a current target situation, *retrieve from long-term memory another description*, the base, which is analogous or similar to the target." (Falkenhainer, Forbus and Gentner, 1989 p 2)
- "Mental experience is full of moments in which a current situation reminds us of some prior experience *stored in memory*" (Gentner, 1989 p 199) and,
- "the chronological first step in an experiential learning sequence is *accessing the potential analog*." (p 200)
- "Analogical problem solving involves three steps, each of which raises difficult theoretical problems. The first step involves accessing a plausibly useful *analog in memory*…" (Holyoak and Thagard, 1989 p 242)

Not all researchers describe analogy in this way. Anderson and Thompson (1989, p 267) note that the base of an analogy can come from someone's "own past… the behavior of another…or it might come from adapting an example given in a textbook. The source for the analogy can be either an explicit experience or a generic or schemalike representation." However, explicit reference to generated analogies as having a base that is constructed rather than recalled is rare.

Prototypes in categorization

Categorization research has a similar history, beginning with theories of category representation as static things stored in memory and recalled for the purposes of judging category membership. Though there is no single theory of prototypes and the graded structure of categories, it was originally argued that a category was represented by a single representation, which was an amalgam of all exemplars stored in memory. Judging whether or not a new item belongs in a category involves comparing it to this amalgam. And this involves recalling all known instances of the category to construct a "typical" exemplar that is "a unified representation rather than separate representations for each member." (Murphy, 2002 p 42) To address concerns with this initial theory, the idea of "feature combination" was added, in which features that are averaged together are first combined, so that "

> people keep track not just of individual features but configurations of two or more features. For example, perhaps people notice how often bears have claws *and* eat garbage, or have fur *and* are white – that is, combinations of two features. (Murphy 2002 p. 45)

Concerns with the computational demands these theories make on memory and recall, schema were introduced. A schema is "a structured representation that divides up the properties of an item into dimensions (usually called *slots*) and values on those dimensions (*fillers* of the slots). Features of exemplars were then stored with a given weight into particular slots. An alternative to this (typically called the "prototype view") is the exemplar view, in which every instance in memory is used in the construction of a category rather than the average of these. While both the prototype and the exemplar view proved generative and had great explanatory power, their representation of mind was problematic and the categories they sought to describe proved to be quite narrow, as Barsalou's research in *ad hoc* categories and point-of-view categories shows.

Construction of the prototype

Barsalou's (1983) studies of "ad hoc" categories addressed categories that cannot be interpreted as fixed cognitive structures, such as "foods not to eat when on a diet," or "things to do at a convention." These categories, which maintained the phenomenological properties of more conventional categories (such as a graded structure), could not be explained simply using the exemplar and prototype theories. Surely, Barsalou argued, one does not store information on such detailed categories but rather constructs it. In later research (Barsalou, 1987) extended this idea, asking participants to take the point of view of a professor, Chinese person, or "redneck" in judging membership in categories. Again, these categories displayed a phenomenological consistency with conventional categories but, again, could not be stored representations. Barsalou argues that "rather than being retrieved as static units from memory to represent categories, concepts originate in a highly flexible process that retrieves generic and episodic information from long-term memory to construct temporary constructs in working memory" (Barsalou 1987). This is not meant to imply that there is not stable knowledge in long term memory, but rather that the concepts in working memory – the ideas that are pondered, discussed, articulated and reasoned with – are temporary constructs and, as such, sensitive to context and goals and inherently unstable. This interpretation of categorization Murphy (2002) contrasts with the prototype and exemplar views, referring to it as the "knowledge view," in which "part of categorization and other conceptual processes may be a reasoning process that infers properties or constructs explanations from general knowledge." (Murphy, 2002, p 60-61)

It is this picture that is missing from most analogy research. In part, this is because the focus of analogy research on how people understand a given analogy – in which case the base of the analogy is present, and one must recall information about that base. It is also due in part, perhaps, to the analogy of the mind to a computer in which context and knowledge construction is irrelevant. However, when paying attention to the analogies that students create when discussing scientific ideas, these analogies are not always drawn to a well-understood base. Rather, the base may be a construction, as with our representations of categories.

Construction of the base in student-generated analogies

In the transcripts above, bases that are clearly not recalled from memory are most profound in the beanbag transcript. In line 64 of this transcript, Connor has predicted that the beanbag will fall backwards and has drawn an analogy to dropping a baseball bat. When the teacher asks "Why do you think it fell behind?" He, surprisingly, notes "Actually it didn't mostly." And then he selects a more appropriate analogy: "if you were on a bus and you had uh, this little leaf that you found, and the window was open, and you drop it, it will go – it'll be going backwards." While it is possible that he has dropped a "little leaf" from a bus window, he does not claim to have done so and it is reasonable to imagine he hasn't. And in line 91, his suggested analogy "What if you did it with a rock?" is based more on a sense of theory than a past experience. Instead of recalling this experience from memory, he is constructing it from "a reasoning process that infers properties or constructs explanations from general knowledge" (Murphy, 2002 p 61) – as has been argued happens in the construction of representations of categories. Kamran, in line 154 (transcript 4), makes this searching for a representation from principles (rather than from memory) clear as he reasons through possible analogies: "A rock is different, a rock has – it's also like, it's solid, but it's not that a leaf isn't solid, or a feather isn't solid. A feather – but you have to – it's very small, and it's very like thin, so you kind of say like solid. But anything hollow, like if you have a paper box…"

A second example of such construction of the base of the analogy comes from the Physics 115 course. Students were asked to make sense of several phenomena of circuits. In one course, an analogy was suggested: imagine a vacuum cleaner sucking up beads, and the light bulbs were like small filters in the tube of the vacuum cleaner. In another course, the analogy was drawn to a hose that is already full of water (so that it takes no time for the bulbs to light) that has small holes in it (which represented the light bulb). In each case, the students are seeking to explain their reasoning via an analogy that they have constructed rather than one they are simply recalling. Again, this underscores the fact that students are not mapping from a well-understood base onto a less-understood target. The consistency of the constructed bases of analogies will be explored in the following chapter, in which I will show that these analogies are constructed from the schemas or p-prims that the students have activated; for now it is important to note that, consistent with the spontaneous construction of categories, the base of an analogy can be a spontaneous construction.

A final example of the constructed base of analogies comes from two undergraduate students who are trying to solve a problem in their quantum mechanics homework assignment. In this problem, they are asked to find the total angular momentum, which the first student, Ben, believes you can answer from first principles. Anselm argues that understanding a simple case does not necessarily mean that you will be able to solve the more difficult problem, and explains this using a constructed (as opposed to a recalled) analogy (transcript 5, lines 15 – 27)[2].

> Ben: We should be able to figure this out from today's lecture.
> Anselm: No you shouldn't.
> Ben: He's gonna explain in detail probably Wednesday how you actually get to J [the total angular momentum].
> Anselm: But see you're doing the wrong thing. 'Cause you're assuming that if you have the example: "suppose there's a charge here, what's the electric field due to it?" You can figure out – suppose you have Bugs Bunny, and he's charged, what's the electric field around his ears? Alright? Because you have a simple example when they're both the same, you're not going to be able to figure out exactly what you're supposed to do when the rules weren't the same.

I will revisit this transcript below for its evidence of a variable representation of the base of the analogy – here I would just like to note that Anselm's analogy, "suppose you have Bugs Bunny, and he's charged, what's the electric field around his ears," is not a problem that these students have been assigned in the past and tried to solve. Rather, Anselm is constructing this as a representation of a category of problems that cannot be solved from first principles. The category is an ad hoc construction and its representation, Bugs Bunny's electrically charged ears, are similarly an ad hoc construction. Constructed, I argue, by categorizational reasoning; and clearly not a map from a known base to an unknown target.

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[2] Ray Hodges, who was a TA in the room with the students at the time, aided in this interpretation of these comments.

Near and far transfer analogies

Research on prototypes and research on transfer

The initial research on categorization established a graded structure of categories, in which some members are recalled more quickly and with greater frequency than others, are judged to be better exemplars of the category and are recognized as category members more rapidly than others. Theories behind these effects are varied and will be explored in the following chapter but, as explained in the above section, it is not due to simple feature matching, but seems to be rooted in reasoning processes and explanations.

Analogy research has shown that near-transfer analogies are far more easy to achieve than far transfer analogies – where near-transfer refers to analogies that are within-domain or have similar features, while far-transfer analogies are those that bear little superficial resemblance to one another. As explained in the previous chapter, however, this may be an effect of the particular style of research being conducted and the lack of meaningful context in which the analogies are situated. And, contrary to this research, "far transfer" analogies do occur in student discourse and are not uncommon.

If one interprets analogies as categorization, then perhaps the ideas of near and far transfer are not relevant. Instead, one would expect the base of the analogy to be, instead of superficially near, prototypical of the category. In this section I will present evidence that the base of analogies are not chosen for the similarity of features or "nearness." Arguing that the choice is, instead, prototypical requires appeals to theoretical considerations that will be addressed in the next chapter.

Examples from student-generated analogies

Returning to the cup/water and cat/basket set of analogies, Miranda (line 59) claims to have done something that is quite similar to the case in question (involving cups, water, and dropping), but her initial analogy to explain her reasoning came from a much less similar experience. In line 25, to explain why she believes water will not spill from the cup as it falls, Miranda offers the analogy of spinning her toy cat overhead in a basket. Later, in line 59, Miranda says: "I've also done that in the bathtub when you've got your cup, I'll like I'll fill it with water put my hand and drop it the water stays in until it hits the bathtub and then it goes everywhere." If the base of the analogy is arrived at through a process of retrieval from memory, as many models of analogy imply, one would expect near-transfer before far-transfer, as the similarity of features would be key in retrieving the analogy. If, instead, the base of an analogy is a construction from this categorization, one would expect a base that is prototypical of the category it is asserting; near and far transfer are not significant questions in this framework. Rather, that the cat/basket analogy is chosen first, is much more convincing and is referred to repeatedly in the classroom can be understood by its prototypicality (or centrality) in the category it serves to describe. Additionally, concerns that Miranda is "making up" the analogy to the cup in the bathtub (this concern has been voiced in discussions with others regarding the analogy) are not important: given that Miranda chooses these two analogies, regardless of whether they are experienced or fabricated, she does so in this order and the class responds to them in this way.

Miranda serves as a particularly powerful example because she refers to two analogies and chooses the "further" analogy first and it is this analogy that holds sway in the classroom and is repeatedly referred to by the teacher and students. Far transfer analogies are not at all uncommon. Other examples from analogies above are:

- comparing a cup of water to a toy cat in a basket
- envisioning electrical charges in metal as fish in a fish bowl
- drawing an analogy between motion of charged particles in Styrofoam and the motion of water through a sponge
- drawing an analogy between motion of charged particles in metal and using stepping stones
- comparing dropping keys on an *x* to hitting a rock on your bike, and
- explaining your approach to solving a total angular momentum problem to solving a problem of the electric field around Bugs Bunny's ears.

While many of the above analogies are creative and intriguing, none are outside of the bounds of "normal" conversation in science, and in many cases a superficially "closer" analogy could seem *too* close and a more strange statement to make than the far transfer analogies. In the next chapter I will argue that these analogies – the "far" analogies – are appropriate and, indeed, expected over near transfer analogies because of their relationship to the category that they serve to represent.

Variable representation of the base

In an effort to understand analogies, the majority of research from cognitive science and education has focused on the comprehension of analogies provided by the researcher or teacher, or the application of a desired analogy (for example, in Holyoak and Thagard's study of transfer). Such studies limit the variability of representations of concepts that researchers can observe. The study presented here originates in research on student inquiry in science classrooms. These classrooms place a premium on student reasoning and explanation of ideas, and, as such, allow for student-generated analogies (which are far more rare in a classroom with a focus on content goals over process goals).

In this section I will present two different kinds of analogies: one set of analogies are presented to explain different ideas about the mechanisms of a scientific phenomenon; the second set are analogies used to explain the speakers' conceptions of the epistemological *type* of scientific phenomena – that is, what is the nature of knowledge that applies to this phenomenon. In each case, the representation of the concept to which the analogy is drawn is chosen from among many possible representations, and categorization, because of its fluid nature and flexibility, can explain this choice of representation.

Variable representation: Example 1

In the following transcript, there are multiple possible representations that the base can take, and the one that is taken depends on the conceptions of the target. While not entirely in discordance with structure-mapping (the process of alignment could be considered choosing the representation), a categorization framework shifts the importance and nature of analogy; when someone says "a is like b" they are not saying: "the structure of this one thing, b, has a lot in common with the structure of this other thing, a." Instead, the assertion of analogy is more akin to "*a* belongs to a class of things typified by *b* – it's the same *kind* of thing." Where a "kind of thing" defines a (often ad hoc) category and more may be brought to bear on *a* than just the relationships that exist in *b*.

This first transcript below is of non-science faculty at the Governor's School of North Carolina. In the lounge of the faculty dorm, they are discussing what happens to a rock in space as it receives energy from the sun: will it heat up indefinitely or only to a certain point? And if it only heats up to a certain point, why does it stop there? This rock is referred to as “David” because of a previous conversation about the differences between humans and statues (namely, Michelangelo’s “David”) in space. Marc is content to say that David will reach a certain temperature and stay there, and explains this using an analogy. Note that Marc prefers a “water” analogy of light, and is able to take on a “money” analogy of light that is contradictory to Vic’s “money” analogy of light. This demonstrates that, one, the choice of base in an analogy is one of ontology and, two, the base can shift representation according to the ontology ascribed to the target (transcript 6, lines 471 – 498).

Marc: Okay– let’s – let’s say David is in a shadow, right? Okay- he enters the sun. The sun bombards him with all this energy right? So in a second it’s now at 5 degrees. Can it radiate heat that fast? No. So in the next second it’s 10 degrees. It’s now radiating a little bit more heat but there’s more energy coming in. So it gets to 15 degrees. But at some point it’s radiating enough heat to stabilize at 20 degrees.
Steve: But why?
Cameron: What?
Marc: Or let’s think of think of like a, think of like a basin, ok? Think of a tub. With the drain open, okay? The drain is open. Now if I open the spigot [Uh huh.] – if I open it too slow then the tub doesn’t fill. But if I open the spigot fast enough there’s water filling up the bottom, and yet some is also draining out, right? [Right.] If I open the spigot up fast enough it doesn’t matter if the bottom is open, the top will overflow but at some point if I reach the right point the tub could stay at a certain level, even if water’s going in and water’s going out, right? If they came in at the same rate [Steve: Right, but –] the tub would fill up.
Steve: But that’s – what’s David’s drain?
Vic: That’s – this is my question. What’s David’s drain?
Tom: Well, what’s the sun’s drain? The sun is clearly radiating heat and energy.
Marc: Yeah I mean that’s just the –
Steve: The sun is radiating *light*.

The conversation continues, and over the next three minutes Marc suggests that things radiate – it’s just what they do; like a drain and like the sun, the rock gives off “radiation and stuff." To explain why we can no longer see the radiation when the rock re-radiates, Marc offers that the light changed from a visible form to a non-visible form. But how "ROYGBIV" (the colors of the rainbow) become "infra-ROY" bothers Vic. The analogy of light as water and a rock as a tub contrasts with the analogy that Vic invokes to point out a problem in Marc's re-radiation explanation in the following transcript (transcript 6, lines 1038 – 1054).

> Vic: Wait wait wait – every – everybody is payin' me money. Everybody is paying me money in different forms – in dollars, five-dollar bills, twenty- dollar bills. [Marc: Okay.] I'm savin' all of my one dollar bills that I don't give away – I do not spend any of my dollar bills on anything ever. Which means that I am gradually accumulating one-dollar bills – even if I'm spending it in fives and tens and twenties. So what do I do when I end up with a thousand dollars in one-dollar bills that I don't know what to do with?
> Marc: I'm gonna change that analogy [Others: Groan.] – or I could keep it! I could keep it! Okay? I'll keep it. Fine – you know what I'm gonna do with those one dollar bills?
> Vic: Tell me.
> Marc: Well – those dollar bills become – you, you spend 50 cents of it in terms of heat and you throw the other 50 cents of it away but we can't see those 50 cents because we're only attuned –
> Tom: You're losing the analogy.

The choice of this analogy is a largely ontological choice: Marc has a "water-like" ontology of light and one can imagine that, just as turning a cup of water into two half-cups of water needs no mechanistic explanation, turning red (a high energy wavelength) into infrared (a lower energy wavelength) does not require further explanation – it happens "by the virtue of your existence." Marc is making a claim about the *kind of thing* that light is – it belongs to the class of things that water belongs to. This class could be described as a conserved quantity that does not come in discrete chunks and flows easily from one "container" to another. Vic has a different conception about the *kind of* *thing* that light is – one that is organized in discrete quantities and matches the category that currency might belong to: net wealth does not count quarters as different from dollar bills, but in terms of actual objects, they are physically different and do not "mutate" into one another. That this analogy is a statement of categorization (the *kind of thing* that light is) is evident in the objection that Tom believes Marc "loses the analogy" when he violates this ontology. Marc, though he wants to "change that analogy" is able to take it on by representing money in as a "fluid" ontology. It is reasonable that money could be conceptualized in the manner Marc intends: when conceiving of someone's bank balance, it makes sense to think of money as belonging to the ontology of fluids: if I deposit a quarter my bank will certainly allow me to withdraw a penny. And gas stations routinely charge to the tenth of a cent (or at least to the nine-tenths!). Structure-mapping and other interpretations of analogies that assume a particular conception to the base of an analogy miss the point that the claims are being made to signify a *class* of objects, and that a base and target can have multiple representations and belong to several different classes (or categories).

Variable representation: Example set 2

In this section I present three transcripts: the first two are conventional analogies – the "tree in the forest" conundrum (albeit with slightly different features), and "apples and oranges" – and the third is a novel analogy regarding Bugs Bunny and electric fields. The first two analogies are intended to establish the categorization model and provide a means of interpreting the third analogy: if the first two are instances of categorization, as I believe is apparent, then so must be the third. And, as with the variable interpretations of "money" (as fluid and divisible or "hard" currency), the base of these analogies may be interpreted in many ways. Furthermore, to echo a prior claim, the third analogy is novel and cannot be argued to be a well-understood base that is recalled from memory but rather is constructed on the fly to represent an ad hoc category.

The first transcript is from a conversation in a 5th grade classroom. The class has been discussing light and heat and the relationship between the two. After reasoning that light “contains” heat because sunlight feels warm, Lisa notes that the light from overhead fluorescent lights does not make you hot (transcript 7, lines 86 – 102).

Lisa:	I think that sometimes, well, most of the times, light is not always containing heat. Like, like this light up here, it’s not con – it’s not, its not –
Dashawn:	Burning?
Lisa:	Yeah, like making you hot.
Kyle:	Yeah it’s not making anything hot.
Anna:	But it's just – what if you go up there and touch it? It would – ?
Brian:	That's because your finger is an object. When it hits something it’s hot.
Teacher:	Oh, I see. So you get, there's a reaction when you touch light.
Brian:	But it's also a question like, um, if a door slams – if a locker door slams and no one’s around to hear it, does it make a noise? Because you don't know if – if you don't touch it and the light is making heat and making the air hot. You won't know.

A variant on the standard philosophical question “if a tree falls in the forest and no one hears it, does it make a sound?” is raised here as an analogy to explain that not only does light need to “hit something” to make it hot, but “it’s also a question” of if, in the absence of a measurement, heat may not be a meaningful concept. It is an argument about the kind of thing that heat is. This analogy could be interpreted in a structure-mapping framework in that it maps elements from the secondary onto the primary; one could align the locker with the light, the slamming with the light hitting a finger, and the heat with the sound. But categorization highlights a very different aspect of this analogical reasoning, namely the ontological goal of expressing the *kind* of thing that heat is. The analogy is *not* drawn for the purpose of comparing two items and making a projection, but to make a sophisticated claim about the nature of light and heat.

An epistemological analogy is drawn in the following transcript. The two students are undergraduate quantum mechanics students working on a problem set together. They encounter one problem (determining "J," the total angular momentum) and have trouble making headway from first principles so they try to work backwards from the answer. Ben can kluge together numbers that are present in the problem to arrive at the answer, but the way in which he assimilates these numbers is nonsensical, as he notes in the transcript below (transcript 5, lines 65 – 74).

Ben: All right, look at this – look at this. If you take all the positives and add them together, you get eight-ninths.
Anselm: Oh, oh.
Ben: You take the negative, you get one-ninth.
Anselm: Yeah that's –
Ben: But you're mixing apples and oranges. It's dumb!
Anselm: Yeah that's so messed up, yeah that's not the answer. If I just ignore the fact that I'm in the three-halves one-half and I'm in the one-half one-half and I just add them all together…

Here the assertion of "you're mixing apples and oranges" is clearly not a matter of structure-mapping, but categorization. The "apples" are not aligned to a specific element present in the physics problem. Rather, "apples and oranges" has come to represent a category of dissimilar things erroneously compared, and Ben's statement is a categorical assertion of the type of thing that he was doing. This claim is not new. Glucksberg and Keysar (1990) argued that the interpretation of a metaphorical statement was a process of categorization. As a means of accounting for this theory of metaphor interpretation as categorization, it has been argued (Gibbs, 1992, Bowdle and Gentner, 1999) that conventional metaphors, such as apples-and-oranges, are interpreted as categories, but that interpreting novel metaphors is structure-mapping. In accordance with Bowdle and Gentner's research and the categorization theory of metaphor, the creation and assertion of the conventional metaphor "you're mixing apples and oranges" seems clearly an instance of categorization and not structure-mapping. However, I claim that categorical assertions are also made with novel analogies. Bowdle and Gentner (1999) have argued against that, at least in the interpretation of novel analogies, but perhaps generated novel analogies could be considered assertions of categorization. In the following transcript a novel analogy is used in a similar way to the "apples and oranges" and the "tree in a forest" conventional analogies. The base of the analogy is clearly novel, not well-understood, and invented on the fly, but its role in the analogy is no different from that of the conventional analogies. The elements of the base of the analogy do not clearly map onto elements in the target, and the claim posed by the analogy is not instantiated by projection but by categorization. Again, a categorization model of analogy is far more capable of understanding the role of the base than a structure-mapping model.

The students in the previous transcript continue to work on the problem of total angular momentum (transcript 5, lines 15 – 26). Ben believes that they should be able to determine the answer because they know the constituent angular momenta and have some background in adding these to find the total. Anselm argues that this does not necessarily mean they can solve this more complicated problem, and draws a novel analogy to explain himself, that of the problem first introduced above of the electric field around Bugs Bunny's ears. Anselm's analogy is to say that this problem of adding angular momenta is like finding the field around an oddly shaped object – not because of any similar structures (the charge and Bugs Bunny don't correspond to any particular items in the angular momentum case) – but because you cannot always find the answer to complex problems using knowledge about simple problems. Knowing the field of an electron doesn't mean that you know the field around an oddly shaped object, like the ears of Bugs Bunny. In this analogy, the *structure* of the problem (calculating total angular momentum from components) is only very weakly similar to the structure in the Bugs Bunny scenario (determining the field around an oddly shaped object); the similarity, and thus the analogy, lies in the fact that they are a similar *type* of problem. Furthermore, the base here is created "on the fly" – the idea that we have a stored representation of Bugs Bunny as an odd shape for the electric field to take seems highly unlikely. Far more plausible is the spontaneous construction of an ad hoc category of *things that are more complex than their simple parts*. The analogy is not from a well-understood base to a poorly-understood target, but instead the base is constructed *spontaneously* to represent an ad hoc category – that of problems you cannot solve from first principles – and asserts membership in this category. In defense of structure-mapping, it could be argued that the elements being aligned were not the particular elements of the problem at hand (the charge, the Bunny, and the constituent angular momenta), but rather the problems *themselves* are elements in a larger structure. But such a claim would bring us back to the problem of representation. The Bugs Bunny analogy can be represented as a structure in itself, or as an element in a larger structure, and choosing which representation is the one to use is a problem that structure-mapping does not address.

Previous Claims of Analogy as Categorization

The claim of analogy as a categorization phenomenon is not new. The greatest proponents of this theory are Glucksberg and Keysar (1990). Why have their arguments failed and what does this dissertation bring to bear that others have not? First, I argue that past claims are overwhelmingly with regard to the *interpretation* of analogies and the claim I am making is about the assertions made by a *generated* analogy. Interpreting analogies allows for a much more narrow range of representations than generating analogies does. Second, as noted by Gentner, Bowdle Wolff and Boronat (2001) the "category-based approach is 'localist:' it assumes a metaphor conveys a categorical relation between a particular pair of terms. Thus this approach addresses single metaphors and not extended systems of metaphors."

As demonstrated above, I am not making "localist" claims with regard to analogies. Rather, I will argue in the following chapter that analogies assert categories based on schemas: categories are defined only within a particular cognitive model, and this cognitive model carries with it a quite extended schema. Previous arguments for a categorization model of analogy used a far more classical model of categorization. The following section addresses a final phenomenological property of analogies – one that is not particularly demonstrative of the categorization framework at first glance, but within a particular ontology of mind, together with a current understanding of categorization, is particularly revealing of the reasons why we use analogies and the cognitive work that they do and is strongly supportive of a categorization framework

Analogies as Negative Assertions

In this final section on phenomenology, I demonstrate that analogies are asserted as an alternative to another way of understanding a particular phenomenon. In part, this is a *definition* of analogy that distinguishes analogy from other forms of similarity, but it is a definition that arose from the data.

In observing what seemed to be analogies and an effort to understand the cognitive work that these insightful moments of analogy did for the students, it became clear that what I understood to be analogies are the statements of similarity that are an *unexpected* similarity. This is a matter of convention, but one that, as I will demonstrate in the following chapter, is a rather powerful convention that is consistent with a particular ontology of mind and understanding of student reasoning.

<u>Violations of expected schemas</u>

In *Women, Fire and Dangerous Things,* Lakoff (1987), who argues that our categories derive from and are defined within cognitive models, notes that one indication of cognitive models is the use the term “but” – as in, “she’s a mother but she has a job.” Such a statement makes far more sense than “she’s a mother but she doesn’t have a job” – which sounds strange. He argues that, to understand these statements and why one sounds so strange, we must turn to the idea of the cognitive model. “Mother” exists in a complex model of nurturance and work, and “working mother” is defined relative to this model (Lakoff, 1987 p 80):

> A *working mother* is not simply a mother who happens to be working. The category *working mother* is defined in contrast to the stereotypical housewife-mother. The housewife=mother stereotype arises from a stereotypical view of nuturance, which is associated with the nurturance model. According to the stereotypical view, mothers who do not stay at home all day with their children

> cannot properly nurture them. There is also a stereotypical view of work, according to which it is done away from the home, and housework and child-rearing don't count. This is the stereotype that the bumper sticker "Every Mother Is a Working Mother" is meant to counter.
>
> The housewife-mother stereotype is therefore defined relative to the nurturance model of motherhood. This may be obvious, but it is not a trivial fact.

I mention this because the analogies that have been presented in this chapter all have this "but" quality to them. As in, "the cup is overturned but it doesn't spill" – which makes far more sense than "the cup is overturned but it spills." As Lakoff says, this may be obvious, but it is not trivial. In the following chapter I will explore why this is not trivial – how it can inform us about cognitive structure and our cognitive models of the world, and then I will revisit this again in considering what it means for education. Here I present it as a final phenomenological property of analogies – student generated analogies in science are "defined in contrast" to expectations, just as "working mother" is defined.

Examples from student-generated analogies: Analogies as negative assertions

The analogies presented in this chapter are as follows:

- an overturned cup of water does not spill like other overturned cups of water, but keeps the water inside, like a toy cat swung overhead in a basket (transcript II),
- density of an object enables/enhances the motion of charged particles as opposed to hampering it, just like a countertop lets water flow while a sponge doesn't, or stepping stones must be closely spaced to allow you to step (transcript I),
- "authenticity" is not a property of an activity, but is a more "interactive" adjective – one that is not solely an attribute of curriculum, but arises from the interaction of the student and community with that curriculum, just as worship is an activity that requires a practitioner and a community of practice (transcript 3)

- dropping a beanbag is not like (at second glance) dropping a bat, but can be understood as dropping a leaf from a bus, or
- it is not like dropping a leaf from a bus, it is like dropping a rock from that bus (transcript 4),
- a quantum mechanics problem is not one to be solved from first principles, just like you could not use a simple field equation to find the field around Bugs Bunny's ears (transcript 5),
- a rock is not just a container of heat but also gives off heat, like sinks not only hold water but also have a drain (transcript 6),
- light cannot be received at one frequency and given off in a different frequency, just as one cannot be received a quarter and turn it into dimes and nickels, or
- light can change from red to infrared, just as one can have a dollar's worth of wealth and spend only fifty cents (transcript 6),
- in order to determine if light contains heat you must put your finger in the light, just like the question of sound in the absence of a listener (a door slams and no one hears it – transcript 7), and
- numbers normally can be added together or multiplied unproblematically, but when these numbers mean something (as in a quantum mechanics problem) adding these numbers might be akin to mixing apples and oranges – it doesn't make sense (transcript 5).

In each of these analogies, they are (perhaps implicitly) not only a claim of similarity – the cup of water is like the cat in the basket – but equally, if not *more* significantly, they are a claim of dissimilarity. They arise as contradictions to what is expected. Numbers usually can be added unproblematically (of course, this is only true in a mathematics classroom and rarely, if ever, true when applied to life); overturned things usually spill; objects are usually seen as generators of energy or receivers of energy but not both – not a tub with a drain; whether or not something happened is not usually contingent upon someone being there to observe it. The way in which this plays into a categorization framework will be explored in greater detail in the following chapter. For now, I just would like to note that this property of analogies is not explained by structure-mapping and other theories of analogies. When it is accounted for, it is added on in an ad hoc manner – by assuming that context or goals is significant and needs to be accounted for – but accounted for in a somehow distinct way (Gentner and Markman, 1997). In their model of analogy, this phenomenology is not inherent to the analogy, but part of the context. In the following chapter, I will argue that it is fundamental to analogy and to the role that analogy plays. Furthermore, it allows for a definition of analogy that distinguishes analogy from routine categorization and similarity.

Conclusion

This chapter, which details the similarities between student-generated analogies and properties of categorization, may seem to disregard the adage: "Correlation does not imply causation." Categorization and analogy are both related to similarity, so they *should* have some phenomena in common – but that does not imply that they are the same thing, arise from the same cognitive mechanism. The following chapter is designed to address causation by introducing an ontology of mind that can account analogies as arising from the same cognitive mechanism as categorization – the only distinction being that analogies offer an alternative categorization to what is expected. The correlation between analogies and categorization are summarized below.

Analogies that students spontaneously generate in science classrooms are often presented in multiples: analogies that are all members of a more general class of phenomena, in which the generated analogies are in agreement with one another, or analogies that are tweaks from one to the next, representing a class of phenomena that bear a family resemblance to one another. These analogies are often "far transfer" analogies that bear little superficial resemblance to their target. They may be constructed on the fly as opposed to recalled from past experience. And the base of the analogy may have a variable representation that changes as the analogy is negotiated. These phenomenological properties of student-generated analogies reflect properties that are representative of categorization phenomena: categories have multiple members and are often related not by strict rules or similarity of features, but a family resemblance that links the various members of the category. Categories are represented by a category prototype, which can account for the prevalence of "far transfer" analogies. They are not stored representations that are recalled, but rather are constructed in a flexible process.

Gibbs, in his article refuting Glucksberg and Keysar's (1990) theory of analogy as a categorization phenomenon, claims (Gibbs, 1992):

> Most metaphorical expressions instantiate, sometimes in spectacular ways, preexisting metaphorical mappings in long-term memory whereby knowledge from a target domain is partially understood in terms of a dissimilar source domain… Metaphors do not simply arise out of temporary, ad hoc categorization processes perhaps to meet particular communicative purposes. Instead, metaphor is a fundamental characteristic of how people categorize and makes (sic) sense of their experience. Verbal metaphors…reflect particular instantiations of metaphorical categorization schemes in long-term memory.

These claims take into account the systematicity of metaphor and polysemy (one word with multiple, related meanings) and are designed to address the more common metaphorical expressions and not spontaneously generated ones.

However, I would like to argue that these claims *cannot* be extended to spontaneously generated analogies. In light of the above analogies from scientific discourse, such as Bugs Bunny, light-as-currency, and dropping rocks from buses, these claims of metaphorical expressions as “preexisting metaphorical mappings” are clearly not true of analogies in general, and particularly not true of student-generated analogies in science, in which they are often investigating phenomena for which they have limited experience and hence no established metaphorical mapping.

Perhaps this inconsistency between the findings from studies of metaphor and the study presented here of student-generated analogies in science is due to inappropriately conflating the two – established metaphor and spontaneously generated analogy. Metaphors, such as the parallels between the ways in which we discuss arguments and the ways in which we discuss war, are ubiquitous in the English culture and apparently “preexisting,” while a student inventing a language for discussing quantum mechanics or falling cups of water must be somehow distinct from using a common language to discuss arguments. However, if I conflate these here – metaphorical expressions and student generated analogies – it is because the literature is unclear on the division between metaphorical expressions that are pre-existing and those that are more akin to student-generated analogies in science. At best, the literature virtually *defines* analogy to be structure-mapping and puts metaphor on a distinct footing because of this definition – but such a definition rules out many of the instances of analogy that are discussed here. This does not negate the fact that metaphor and analogy are a fundamental characteristic of how people categorize and make sense of experience – but such an idea need not imply that metaphors and analogies (that is, the mapping of two domains) and their associated categories (that is, the set of phenomena that are consistent with a particular analogy) are fixed representations. Instead, I will argue in the following chapter that what *is* stored in long-term memory are particular schemas that may be combined in any number of ways and give rise to what appear, at times, to be stable categories.

In a purely phenomenological sense, the properties of analogies outlined above are consistent with properties of categorization. Categorization does not require that there be stored representations of concepts or categories that we recall, but rather that "concepts originate in a highly flexible process that retrieves generic and episodic information from long-term memory to construct temporary constructs in working memory" (Barsalou 1987). In the following chapter, I will outline an ontology of mind that is consistent with the findings from categorization and can account for the analogies described here.

Chapter 5: The Ontology of Mind

Introduction

This chapter takes the properties of student-generated analogies in science that were detailed in the previous chapter and introduces a theory of mind that can account for these, explaining how a particular ontology of mind can begin to account for findings in categorization and details why these findings should be expected to apply to analogies. I begin with an introduction to the idea behind "ontology of mind:" what are the things that researchers have attributed to the mind and what does research show to be the fundamental building blocks of thought? I first review research in cognitive science and education that treats the mind as "having" representations for concepts, and then introduce challenges to this ontology of mind. I introduce an alternative to this ontology, in which smaller schemas are the things the mind "has" and these building blocks are put together into larger models that are in turn used to construct representations for concepts. The consistency of this understanding of the mind with categorization and, in turn, analogies is then explored.

History of Ontology of Mind and Description of the Chapter

Perhaps drawing from an analogy to computers, concepts have long been treated in cognitive science and education as internal mental representations that are then acted on by computational processes. Such research would say that a student "has" a concept or "has" a misconception. This assumption of concepts as stable representations and its implications on the ontology of concepts in the mind has been called into question in the last decade in several fields, most notably by a paradigm in education of situated cognition. Situated cognition claims that knowledge is intrinsically situated, “being in part a product of the activity, context, and culture in which it is developed and used” (Brown, Collins and Duguid, 1989) and, as such, one cannot discuss what “thing” a student knows – the very ontology of knowledge as thing is what they call into question. Despite these concerns about mental representations, the most widely accepted and used model of analogy is Gentner’s 1983 structure-mapping theory, a theory that ascribes representations to concepts and then acts on these. But there are multiple ways in which we represent the concepts used in an analogy as demonstrated in the previous chapter. “Money” can be pictured as a fluid kind of substance or a hard currency kind of substance. “Apples and oranges” can refer to apples and oranges or to a more general category, just as “bugs bunny’s electrically charged ears” can mean just that, or can mean a strange shape with an intractable solution. As such, mapping the structure of a concept in an analogy must first entail *creating* a representation that can be mapped, a process that structure-mapping does not explicate.

If the mind does not have static, unitary representations for concepts, what *is* the ontology of mind? Alternative to the unitary ontology of mind that is inherent to many models of analogy is a manifold ontology, as expressed by schema theory, idealized cognitive models and phenomenological primitives. These theories have been employed in explaining the graded structure of categories. As an alternative to structure-mapping, I argue that *categorization*, in the modern, non-classical sense (arising from cognitive models), more effectively describes analogical assertions – not only because of the phenomenological similarities between categorization and student-generated analogies, but also because of the ontology of mind implicit in a categorization framework of analogy.

This chapter is divided into two parts. In the first, a theoretical account and literature review, I will sketch the basic idea behind structure-mapping, highlighting the assumptions that it makes about the representation of concepts in mind – assumptions of the ontology of mind. I will contrast these assumptions with concerns from cognitive science, linguistics and education that argue against stable, large-scale structures of mind, and detail the alternative theories that account for this manifold ontology. I will then in the second part turn to student-generated analogies in science and show how these theories, in particular phenomenological primitives and idealized cognitive models, are consistent with these analogies.

Section 1: A theoretical account of the ontology of mind

Structure-mapping

As explained in the previous chapter, structure-mapping theory argues that interpreting an analogy involves both alignment and projection. The process is described in Bowdle and Gentner (1999):

> Structure-mapping theory assumes that interpreting a metaphor involves two interrelated mechanisms: alignment and projection. The alignments process operates in a local-to-global fashion to create a maximal structurally consistent match between two representations that observes one-to-one mapping and parallel connectivity (Falkenhainer, Forbus and Gentner, 1989). That is, each object of one representation can be placed in correspondence with at most one object of the other representation, and arguments of aligned relations are themselves aligned. A further constraint on the alignment process is *systematicity*: Alignments that form deeply interconnected structures, in which higher-order relations constrain lower-order relations, are preferred over less systematic sets of commonalities. Once a structurally consistent match between the target and base domains has been found, further predicates from the base that are connected to the common system can be projected to the target as *candidate inferences.*

The claims from this theory that I intend to highlight are the single representation of a structure that is derivative *of* the base, and one-to-one alignment of objects in that representation. In particular, this theory assumes that concepts have representations that are then operated on; in a sense, the base of the analogy is primary and the structure – *a* structure – “belongs” to that base. The variability and the stability of this structure, the representation, are not explicitly addressed in the original theory, nor is it necessary to assume that the structure is a stable and invariant property of the base – however, the associated computational model of structure-mapping, the Structure Mapping Engine (Falkenhainer, Forbus and Gentner, 1989) consistently presents these representations as unitary cognitive structures belonging to the base. But just as research from categorization reveals that the concept of a leap has no simple propositional structure and no unitary cognitive representation as a categorical construct, neither will “leap” or other concepts have a single representation and structure when applied in an analogical construction. Defining the representation of a concept for mapping in a structure-mapping theory is not a simple act of recall as the theory implies – it is not our concepts that have stored representations that we simply recall, but rather our schemas that do or do not apply to concepts. Failing to address this presumes either that there are stable, unitary representations or that the retrieval of one representation from the manifold that exist is not a crucial element to analogy – both of these assumptions are challenged below, first in a review of the literature on variability of conceptual representation and then I turn to student-generated analogies and evidence against stable, unitary representations of concepts.

<u>*The arguments for variability in conceptual representations*</u>

Research from psycholinguistics, education and categorization has identified manifold representations of concepts and argued that when concepts are *manifested* as singular, stable structures this does not imply a unitary structure to concepts in the mind. These findings are further detailed below.

Psycholinguistics

Recent psycholinguistic theory has suggested that the mental lexicon, instead of being organized in a dictionary-style, is far more like a thesaurus. That is to say, the way our minds represent words is not so much as obeying rigid definitions with propositional structure, but rather the meaning of one word is tied to a network of related words – words that have appeared in similar contexts, words that have appeared in context with that word, and words that have related meanings. Computationally generated lexical networks have been developed to represent the lexical network of the English language (one example is the well-known Wordnet, by Fellbaum, 1998). These thesaurus-like structures link words in definitions into a network using various algorithms. Gaume et al. (2002), building on categorization research that they summarize as establishing the "conceptual flexibility" as opposed to "rigid and discontinuous categories," argue that words *themselves* constitute categories and contend that these lexical networks weave a "mental lexicon distributed around metaphoric poles." Amin (2001), in a cognitive linguistics study of heat, makes a similar claim about certain conceptualizations "as dynamic constructions at the moment of use," finding that "a stable assignment for the ontology of 'heat' is absent from the layperson's core understanding, but rather emerges in specific explanatory contexts." (p 38) Quinn (1987) has reported similar findings with regard to the concept of marriage as having conceptual flexibility:

> Quinn (1987) has found, in studying conversations about marriage in minute detail, that each spouse in a marriage has multiple, and often contradictory, understandings of what marriage is. But it is common in a discussion of marriage for a spouse to shift mid-sentence to a different understanding which is inconsistent with the one they sentence started out with. (Lakoff, 1987 p 215)

As with claims from situated cognition, these findings counter the relatively frequent assumption in cognitive science that there are single, fixed mental representations of concepts. In drawing analogies between a base and target, assuming a single representation of that base will fall short of explaining the power and feat of the analogical mapping, as demonstrated in the transcripts presented in the previous chapter. Students are able to shift representation of concepts used in an analogy and choose to represent a concept as an epistemological (as with "Bugs Bunny" in transcript 5), ontological (as with "authenticity" in transcript 3) or mechanistic (as with "ice skating" in transcript 1) statement. Categorization, in which categories arise from cognitive models, as I explain below, allows for this flexibility and accounts for the nature of analogical reasoning that students display.

Education

In addressing student difficulties in physics, several researchers refer to common "misconceptions" that students have and propose curriculum to address these (e.g., Doran, 1972; Caramazza, McCloskey and Green, 1981; Griffiths and Preston, 1992; Brown, 1992). Implicit in these statements, and their associated curriculum, is that there are stable, consistent conceptions students have that educators can find and change. However, Taber, in a study of students' conceptions of bonding in chemistry (Taber, 2000), found that students employed different representations to the same concept on different occasions. He reports that the idea that students cognitively ascribe a particular structure to concepts is a reflection of "the researchers' conceptualizations – explicit or tacit – about the nature of cognitive structure." This claim echoes Barsalou's criticism of the paradigm in categorization research that aimed to define the structure that students ascribe to categories (Barsalou, 1987):

> When investigators use linguistic analysis to determine prototypes, definitions, and idealized cognitive models, they appear to assume that there are invariant concepts in long-term memory that need to be fully characterized.

Similar to Barsalou's findings (if you *look* for variability in representations of categories you will find it) Taber found that the idea that students hold a particular conception of a scientific phenomenon is flawed. An individual learner can simultaneously "hold in cognitive structure several alternative stable and coherent explanatory schemes that are applied to the same concept area" (Taber, 2000). A theory of mind to account for these findings involves schema theory, detailed below. I first return to the evidence from categorization research that tells a similar story of variability, and then introduce schema theory, which can account for these findings and can account for the graded structure of categories.

Categorization

Rosch (1973) established that human categories were not, as one might assume, simple "containers" of which an exemplar was either a member or not. Rather, categories exhibit a graded structure with some members being judged more prototypical of the category than others, and a gradience in membership, so that the distinction between a category member and a non-member is not clear. Continued research by Rosch and others was designed to determine the structure of these categories and the origins of that structure. Barsalou's initial research on categorization looked at *ad hoc* categories (such as "foods not to eat on a diet" or "items to take from your house in a fire") and showed that these categories, though certainly not stable categories that are represented cognitively prior to their construction, still possessed the graded structure found in "common" categories. His continued research looked into the stability of this graded structure (Barsalou, 1987). He asked participants to judge the typicality of category members from their own point of view and the point of view of others (such as a professor's point of view) and analyzed between- and within-subject reliability of categorizational structure. The findings point to significant variability in graded structure: participants were able to judge the typicality from others' points of view (occasionally with stunning accuracy). Additionally, the within-subject judgments of typicality varied (with moderately typical category exemplars changing rating the most). Graded structure, Barsalou concludes, is "a highly flexible and unstable phenomenon." Context, linguistic context, point of view, and other factors affect the typicality assigned to category exemplars. Surely, he argues, people do not possess representations in long-term memory of how a professor would assign structure to the category of dinner foods.

The implication on the structure of categories, Barsalou argues, is that "rather than being retrieved as static units from memory to represent categories, concepts originate in a highly flexible process that retrieves generic and episodic information from long-term memory to construct temporary constructs in working memory" (Barsalou 1987). This is not meant to imply that there is not stable knowledge in long term memory, but rather that the concepts in working memory – the ideas that are pondered, discussed, articulated and reasoned with – are temporary constructs and, as such, sensitive to context and goals and inherently unstable. Furthermore, prototypes of categories are not stable properties of categories – these are not the elements that are stored in mind and organize categorization. They arise from cognitive processes on more stable units. But what are the stable units that minds have, then?

Structures in a manifold ontology of mind

Resources

Stemming from findings regarding the variability of reasoning in science, Hammer (2004) has argued against a research paradigm in science education that focuses on student misconceptions and its implicit assumptions on the nature of concepts and mind.

> What sorts of things do we attribute to students' minds? It has become conventional to speak and think in terms of conceptions, naïve theories, and stages of development. These are all attributions of stable properties, and they account well for patterns that can occur in student reasoning. They do not account well, however, for the variability and multiple patterns illustrated [elsewhere].

As an alternative to the unitary conception of mind, he offers what is termed the "resource model" as a more fruitful ontology of mind with multiple, fine-grained cognitive resources that are or not activated. Different conceptions of marriage, as mentioned above, could be considered different *resources* for understanding this concept that are activated at different moments. This is not to say that students cannot or should not have a robust, stable representation of a particular concept, but rather, as noted by Hammer: "Ontology need not recapitulate phenomenology… The cognitive objects we attribute to minds need not align closely with the ideas and behaviors we hope students to transfer." (Hammer, et al 2004).

Idealized Cognitive Models, Schemas, and P-prims

Lakoff (1987) has proposed that categories are derivative of idealized cognitive models of the world (ICMs), "which van be viewed as 'theories' of some subject matter." (Lakoff, 1987 p. 45). These "theories" can be parsed into various schemas or short "scripts" that we have about the world and the way it works: *event schemas* that are abstracted from our experience of certain events, *image schemas* that provide structure for conceptualizations – "schemas of intermediate abstractions [between mental images in abstract propositions] that are readily imagined" (Palmer, 1996 p. 66) – and *proposition schemas*: abstractions that act as models of thought and behavior and specify "concepts and the relations which hold among them." (Quinn 1987)

Schema theory holds that we possess a pattern of associations in our mind that lead to locally coherent ways of understanding and negotiating our world. As described by Rumelhart (1981), schemas are

> the fundamental elements upon which all information processing depends. Schema[s] are employed in the process of interpreting sensory data, … I retrieving information from memory, in organizing actions, in determining goalas, … in allocating resources, and generally in guiding the flow of processing in the system…[Schemas represent knowledge] about … objects, situations, events, sequences of events, actions, and sequences of actions.

And schemas are distinguished from the more generic "models" in Redish (2003, p 13):

> I follow the notation of D'Andrade and call such a pattern a *schema* if it is a "bounded, distinct, unitary representation" that is not too large to hold in working memory. I call a pattern a (*mental*) *model* if it consists of "an interrelated set of elements which fit together to represent something. Typically one uses a model to reason with or calculate from by mentally manipulating the parts of the model in order to solve some problem." (D'Andrade, 1995 p 151)

This is to say: what we do have in our minds are short scripts, sequences, or stories that can be combined to create models. These *are* "bounded, distinct [and] unitary," unlike the phenomena that they may describe. Taber (2000) noted that an individual learner can simultaneously "hold in cognitive structure several alternative stable and coherent explanatory schemes that are applied to the same concept area," namely in the concept of bonding; these coherent explanatory schemes are what I mean by a locally coherent structure – bounded, distinct, and unitary scripts for understanding bonding – while bonding is understood with a manifold set of schemas. (Of course, part of science involves reconciling competing schemas and placing them within a larger explanatory framework that accounts for both – it is in this that Hammer (2004) notes, "the cognitive objects we attribute to minds need not align closely with the ideas and behaviors we hope students to transfer.")

It is only within our schemas that categories are defined and meaningful. As noted in the literature review, the question "is the Pope a bachelor?" is a confusing question. By all definitions of "bachelor" the answer is *yes*, but no one would ever refer to the Pope as a bachelor. Lakoff explains this paradox with an appeal to cognitive models: "bachelor" is defined and meaningful only within a cognitive model (a sets of schemas) of society that has marriage and the schemas associated with marriage – and these schemas that are activated do not take into account our schemas involving clergy. Therefore this category – bachelors – becomes less meaningful and exhibits a graded structure to the degree that the schema in which it is defined does not apply (as in the case of the Pope). And prototypes of our categories arise *from* the concretization of these cognitive models. It is not the exemplars that organize our categories, but the schemas and compilations of those schemas into larger cognitive models that organize (and at times *construct*) exemplars into categories. When discussing prototypes in this dissertation I am not referring to static exemplars around which our categories are organized, but ad hoc constructions and recollections that are organized by the schemas, cognitive models and resources that are activated.

This differs greatly from the representation of concepts from structure mapping and the related computational model. For even if the model took into account a variability of representations, the model still attributes these representations as stored properties of the base and not more abstract, general schemas.[1]

In the model of analogies as assertions of categorization, then, there is implicitly some underlying schema involved. In physics education research, a set of simple,

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[1] For example, noting the lack of variability for concepts described in the Structure Mapping Engine, the following suggestion for incorporating multiple representations is introduced (Falkenhainer, Forbus and Gentner, 1989, p 39):

> The SME algorithm is of necessity sensitive to the detailed form of the representation, since we are forbidding domain-specific inference in the matching process. Existing Al systems rarely have more than one or two distinct ways to describe any particular situation or theory. But as our programs grow more complex (or as we consider modeling the range and depth of human knowledge) the number of structurally distinct representations for the same situation is likely to increase. For example, a story might be represented at the highest level by a simple classification (GREEK-TRAGEDY) at an intermediate level by relationships involving the major characters (i.e., (CAUSE (MELTING WAX) FALL)),and at the lowest level by something like conceptual dependencies. An engineer's knowledge of a calculator might include its functional description, the algorithms it uses, and the axioms of arithmetic expressed in set theory. Unless there is some window of overlap between the levels of description for base and target, no analogy will be found.

primitive schemas that students use has been identified. These, as noted in chapter two, are phenomenological primitives. From chapter two (p. 32, this document),

> They are "the intuitive equivalent of physics laws; they may explain other phenomena, but are not themselves explained with the knowledge system." As defined by diSessa, p-prims are "cued to an active state on the basis of perceived configurations, which are themselves previously activated knowledge structures." In this way p-prims are elements within larger models. P-prims "often originate as minimal abstractions of common phenomena," and are "nearly minimal memory elements, evoked as a whole." By way of example, consider one class of p-prims: the "constraint cluster." This class includes bouncing, supporting, guiding, clamping, and carrying. These p-prims are not fundamental for a physicist (all can be explained in terms of forces) but are often elicited in conversations with students as explanations for physical behavior. The p-prims have a "schematization" such as, for the "supporting" p-prim, "'strong' or stable underlying object keeps overlaying and touching object in place." (diSessa, 1993 p. 216)

Many of the analogies that students express can be shown to have their origin in phenomenological primitives. Below, I will show that the analogies presented in chapter two for their *phenomenological* similarity to categorization can be understood by this *ontology* of mind: they are based in particular schemas and the role of the analogy is to move the target of the analogy from one locally coherent structure to another. First I would like to address a point raised in the previous chapter: analogies as negative assertions, and the distinction between similarity and analogy.

Interlude: A distinction between similarity and analogy

The conflation of similarity and analogy in past definitions

If this is how the mind works – it has stored schemas that become activated and put together in a variety of ways, and these schemas are responsible for our categories, and, as Lakoff (1987) noted, *everything* is an act of categorization:

> Every time we see something as a kind of thing, for example, a tree, we are categorizing. Whenever we reason about kinds of things – chairs, nations, illnesses, emotions, any kind of thing at all – we are employing categories.

> Whenever we intentionally perform any kind of action, say something as mundane as writing with a pencil, hammering with a hammer, or ironing clothes, we are using categories.

then perhaps structure mapping is just a way of detecting a schema that applies. That is to say, structure-mapping involves abstracting a structure from the base that you then map onto the target, and, given that the mind has stored schemas, perhaps "structure" is simply another word for "schema." The schema is the structure and this is mapped onto a new scenario in what we see as analogy, and then the only piece lacking from the structure-mapping story is *how* that particular schema is arrived at, given the manifold that exist. But if this is the case, then *every* act of categorization becomes an act of analogy, as Hofstader (2003, p 506) believes to be the case:

> The triggering of prior mental categories by some kind of input – whether sensory or more abstract – is, I insist, an act of analogy-making. Why is this? Because whenever a set of incoming stimuli activates one or more mental categories, some amount of slippage must occur (no instance of a category ever being precisely identical to a prior instance). Categories are quintessentially fluid entities; they adapt to a set of incoming stimuli and try to align themselves with it. The process of inexact matching between prior categories and new things being perceived (whether those " things" are physical objects or bite-size events or grand sagas) is analogy-making par excellence. How could anyone deny this? After all, it is the mental mapping onto each other of two entities – one old and sound asleep in the recess of long-term memory, the other new and gaily dancing on the mind's center stage – that in fact differ from each other in a myriad of ways.

Consider the diagram below, first presented to me by Redish (research group meeting, 2004) and constructed by Edward Adelson. When participants are shown this diagram and asked which square is darker, *A* or *B*, everyone will claim that *A* is the darker square.

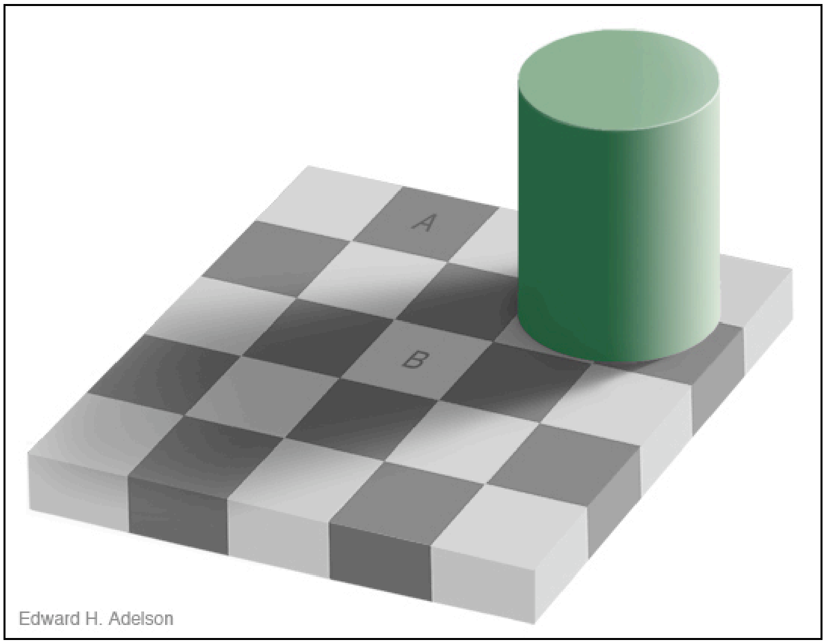

Fig. 5.1

In fact, the squares are the same shade – but even knowing this it is hard (if not impossible) to convince your mind otherwise. We cannot help but run the "schema" that helps us judge the relative brightness of objects. And so, in a sense, we are mapping all of our prior experiences with intensity, shades and shadows onto this new experience. According to structure mapping, *this* is analogy – we have mapped the structure of prior experience (things in the shade are lighter than they appear) onto this new experience (*B* is in the shade, it must be lighter); according to Lakoff, this is categorization (we are using a cognitive model and placing this picture into that model); according to Hofstadter, these – categorization and analogy – are one and the same. A similar claim can be made of the students in transcript 2 that believe this new cup of water will spill: they are assuming that *this* cup of water is like all other cups of water – it will spill when overturned. They are mapping a structure or schema involving cups of water onto this new cup of water. But there is something that *feels* different about Miranda claiming that a cup of water is like a toy cat in a basket and the other students who are implicitly mapping their prior experience with cups and water onto this instance of a cup and water.

This distinction between analogy and more “knee-jerk” categorization/ identification of schema is addressed by diSessa (1993), in studying the “Montessori bell conundrum.” In this problem, students are presented with bells made of the same material, same length, same height, but varying widths. Almost without exception students predict (erroneously) that the thicker bells will have a lower pitch. DiSessa reports:

> Although most subjects were ready with analogies – church bells compared with jingle bells, xylophones, musical instruments of various sizes – I was struck that some initially could not produce any example of the phenomenon they identified to be at the root of the situation. This, along with the rapidity and expressed certainty of responses, heightened my confidence that a p-prim (or several) was at stake rather than analogy. (diSessa, 1993)

That is, students are able to make a prediction for the Montessori-bell conundrum *without* any explicit reference to an analogous case. Many students are able to construct, post-hoc, an analogy to explain their reasoning, but some cannot – suggesting that the prediction for these bells was not made with any explicit analogical reasoning between this set of bells and other sets of bells or instruments. DiSessa, accordingly, distinguishes this automatic assumption/prediction from analogy.

This distinction between analogy and p-prim that diSessa makes is not consistent with structure-mapping or other accounts of analogy: while diSessa claims that a p-prim is not an instance of analogy, Gentner’s description of structure-mapping and Hofstadter’s account of the ubiquity of analogy construct a definition of analogy in which any kind of similarity is analogy. And perhaps it is quite fruitful not to distinguish instances of p-prims and schemas from analogy. This is Hofstadter’s approach, and surely understanding the more routine acts of categorization – how we recognize an "a" in handwriting that we have never seen before, for example – can shed light on how we make the more creative feats of imagining a cup of water to be like a toy cat in a basket.

I would like to distinguish the more creative aspects of analogy, those that are powerful for their ability to *shift* from one locally coherent structure to another, from the more routine kinds of activities that our minds undertake automatically and without cognitive effort. This is a piece that is missing from structure-mapping and is acknowledged by its authors, who note that the Structure Mapping Engine (a computational model of structure mapping) finds literal similarity to be the best possible match when determining the soundness of an analogy: when comparing relational structures and disregarding surface features, the literally similar structures will, naturally, be the strongest possible match (Gentner, 1989). Or, as Gentner and Markman note (1997, p 48), " this contrast between analogy and literal similarity is in fact a continuum, not a dichotomy. Yet it is an important continuum psychologically, because overall similarity comparisons are far easier to notice and map than analogical comparisons, especially for novices." However, other researchers have found criticism in this continuum account of analogy, in particular the lack of attention to goals and context. As Holyoak (1985, p 74-75) notes, "even objects that Gentner would term 'literally similar' can be analogically related if a goal is apparent." Commenting on this criticism, Gentner notes "since this is essentially a question of terminology, it may be undecidable" (Gentner, 1989 p 220).

A proposed definition of analogy as a change of schema

It *is* a question of terminology and a matter of choice as to whether or not this is what we mean by analogy and if we would like analogy to exist on a continuum from similarity or be somehow distinct, but I would like to focus on those analogies that take us from one schema to another and take deliberate cognitive effort, and contrast those with more routine categorization that happens cognitively automatically. Both are acts of categorization, but one, analogy, I will use to mean a *re*categorization. In this way, analogy is so powerful because of what Koestler has identified as the "essence of creativity:" being able to view a situation or an object from two different frames of reference, or two 'unrelated matrices of thought' (Koestler, 1964). Or, as Chi (1997) clarifies, "the essence of creativity is… re-representing an entity or a situation from one 'ontological' tree of concepts and categories to another ontological tree of concepts and categories." This recategorization is more profound than considering a person to be both a daughter and a sister and a chef – that is, it is not simply choosing one of a myriad of schemas that apply to a phenomenon, but instead invokes a schema that is at *odds* with the alternative category. For example, considering a cup of water to be unlike most cups of water that do spill, and more like a toy cat in a basket that doesn't.

Using a dial ammeter to measure current, undergraduate students in my Physics 115 course measured the current coming from the battery in the following circuits:

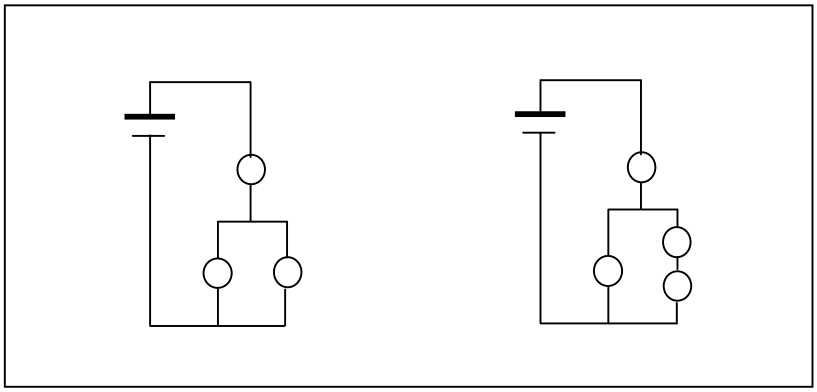

Fig. 5.2: Circuit set-ups for measuring current from battery

Slightly more current leaves the battery for the circuit on the left. Though the measurements were initially taken for another purpose, I later referred to them as a counter-argument to a student's claim that the battery always puts out the same amount of current. But the students claimed – erroneously – that the ammeter readings gave the same value. It's understandable – the dials are difficult to read precisely and students often round – but that alone doesn't explain it, as students will often argue over insignificant differences in readings and each lab group reported the same findings: the ammeters read the same value for the current leaving the battery. Only one student recorded "100+" and "100–" because of the discrepancy in the ammeter readings. Perhaps the students had expectations about what these numbers should be – but this expectation did not come from their knowledge of circuits or experience with ammeters (none had extensive experience with either), but from experiences with phenomena in which the output from the source is not mitigated by the consumer – like rain, perhaps. This can also help explain why students, when handed a bulb, battery and wire, often first try to light the bulb in this manner:

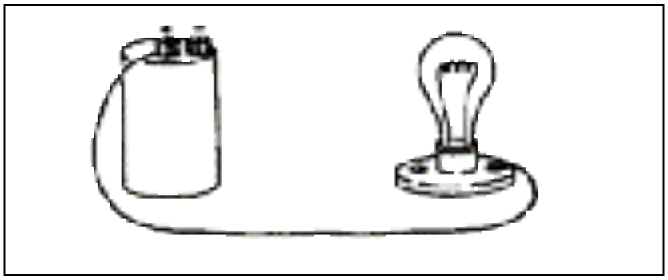

Fig. 5.3: Typical arrangement tried by students

The battery is a source of energy and the light is a consumer of that energy, and the students assume that, as with every other source of energy, you need a path from that source to the consumer. You rarely (if ever) need a path *back*. The students' attempts make sense – they are matching a pattern they have observed before with other sources of energy and mapping it onto a new case. *But is this analogy?* Again, Hofstadter (2002) argues that it is, and structure mapping would say that either this is analogy, or that structure mapping requires an explicit reference to the base – a reasonable argument but also somewhat post hoc.

I argue that this is *not* analogy by definition, because in the absence of such a definition we risk turning everything into analogy. Analogy is a deliberate cognitive step that involves a negative assertion, claiming that *this* source of energy (the battery) is not like other sources of energy.

In this chapter, I am providing the sketch of an underlying cognitive mechanism to account for the phenomenology described in the previous chapter. What are the pieces of mind that can explain student-generated analogies? The themes of findings on the ontology of mind that will be revisited below in the context of student-generated analogies is as follows: if anything is stably stored in the mind in invariant "chunks" it is not large-scale theories or concepts, but much smaller scripts and stories that provide a kind of "alphabet" of sorts for constructing theories. This suggests that while certain schemas may be associated with a particular analogical base, it is more accurate to consider the schema as the fundamental cognitive unit. Or, structure mapping implies that an analogical base "has" – rather objectively – a particular structure. Rather, the theories of schemas, p-prims and ICMs suggest that a particular schema or p-prim is primary and this schema becomes concrete by constructing a base. The base is a representation of a particular schema and is understood and interpreted within that schema.

Beginning, again, with Miranda's analogy of the toy cat in a basket, below I will outline the schemas associated with the analogies that students generate and argue that these analogies are particularly relevant (or prototypical) of that schema.

Section 2: The base of generated analogies as representations of a schema

The analogies presented in the previous chapter for the phenomenological similarities between categorization and student-generated analogies, are presented and analyzed below for the schema from which they derive. The categorical assertions that the analogies make are consistent with these schemas, and the ontology of mind implicit in a categorization framework of analogy is consistent with findings outlined above.

Schemas and p-prims in the cup/water analogies

The transcript from a 5th grade class, discussing what happens to a cup of water as it falls, was first introduced for the phenomenological evidence in support of categorization; in the exchange surrounding this analogy there are multiple analogies presented, the analogy that is first presented is "far" transfer, and it is presented in opposition to the schema other students implicitly apply. I present these analogies in this chapter to make an argument for the reasoning behind these analogies, for the schema in which they are based and how the analogies may be viewed as prototypical or particularly characteristic of that schema.

Having been asked to predict what will happen when an overturned cup of water is dropped from a cookie sheet, a student predicts that the water will not fall out until it hits the ground and uses the analogy to a toy cat being swung overhead to explain her prediction (transcript 2, lines 13 – 26), claiming "I pull it down and it stays in the back [motions that the cat is up at the top] until I stop and then it comes out."

Past models of analogy argue for a one-to-one alignment of objects in the target and base of the analogy that, once made, allow for candidate inferences to be drawn (in this case the candidate inference is that this cup will not spill). Instead, I posit that the function of Miranda's analogy was, first, to identify a different story – one about swinging baskets that, when overturned, don't spill – and used this event schema to reclassify this cup as a different kind of thing. It *isn't* like most overturned cups, she argues – it belongs to a class of phenomena that is typified by an overturned, swinging basket. By understanding the schema Miranda is employing, this analogy is not so much an instance of "far transfer" but instead prototypical of a particular event schema with which Miranda is familiar. The very idea of "far transfer" – which has been the focus of many research studies – may not be the most meaningful concept in studying learning.

Far more relevant in drawing analogies is recognizing that the base of an analogy is the concretization of an appropriate schema, and that base is a prototype – that is, the spontaneous construction of a representation for that schema. The cat/basket analogy is like an airport hub: we arrive here before we arrive at nearby towns – it's an entry point to a certain area. Our minds don't detect similarity solely by matching features. Just as travel distance is measured along roads from airports, and not as the crow flies, it does not make sense to discuss "near" and "far" analogies when you are restricted to moving through the cognitive map along particular schemas and via particular patterns of activations. You arrive at the airport before you arrive at closer towns – it takes less time for me to get from DC to Seattle than to get to Mazama, a mountain town east of Seattle.

Schema

The theoretical and empirical support for this interpretation of Miranda's analogy comes respectively from research in physics education on phenomenological primitives (p-prims) and two phenomena surrounding this analogy: Miranda's gesture during her explanation, and Miranda's choice of base in the analogy. P-prims "often originate as minimal abstractions of common phenomena," and are "nearly minimal memory elements, evoked as a whole" (diSessa, 1993). By way of example, consider a particularly relevant class of p-prims (relevant to the transcript above): the "constraint cluster." This class includes bouncing, supporting, guiding, clamping, and carrying. These p-prims are not fundamental for a physicist (all can be explained in terms of forces) but are often elicited in conversations with students as explanations for physical behavior. The p-prims have a "schematization" such as, for the "supporting" p-prim, "'strong' or stable underlying object keeps overlaying and touching object in place." (diSessa, 2003 p 216)

Miranda is employing the "carrying" p-prim (and its associated schematization) together with noting the upside-down container. Her gestures, in particular, are indicative of this p-prim. With her explanation she begins by miming holding a right-side-up basket, arm at side, and then swung overhead. She repeats this motion again with each successive explanation: the toy cat is held by a right-side-up basket, swung overhead, and held in the bottom of the basket as she pulls down. When she stops pulling (that is to say, she stops the "carrying" part of her actions) the cat falls out.

Prototype

Prototypes are, as defined by Rosch, the first members of a category that you recall, are quickly recognized as members of that category, and can be used to generalize about other category members. With respect to the ontology of mind presented in this chapter, prototypes are not primary, nor do they serve as mental representations of categories; rather, schemas are primary and may be put together together to create a larger scenario – such as the falling cup of water – from these schemas we construct categories, and it is through the concretization of these schemas and categories that we arrive at prototypes. They are constructed on the fly from the schema (or bundle of schemas) that are activated. In terms of understanding Miranda's analogy, it seems likely that the base of the analogy (the cat/basket) is prototypical (in that it is drawn first, used to generalize, and easy to learn). Miranda has a set of schemas that have been activated – perhaps carrying and overturned (and even, perhaps, things that are surprising – one can imagine Miranda thinking: "He wouldn't ask this question unless the answer was something interesting and weird.") – and she makes these schemas concrete and, hence, relatively stable by the construction and assertion of this base, which is latched onto not because of its similarity to the target of the analogy but because it is the most immediate and unproblematic representation of these activated schemas. Miranda, in fact, has experience with more "similar" members of this category but constructs an analogy to the cat/basket first. She refers to the cat/basket as a “rollercoaster” game but does not use a rollercoaster as her analogy, and then claims that the cup of water is like an instance when she dropped a cup of water in her bathtub (transcript 2, lines 55 – 61).

As noted in the chapter on the phenomenology, previous models of analogy in which objects are placed in a one-to-one alignment would predict that Miranda should first draw the bathtub analogy: the features are closer and more easily mapped. In a categorization model in which the category emerges from the associated schema, the swinging basket is naturally a more readily available analogy, as it is, for Miranda, a more prototypical/accessible a case for the schema associated with carrying things upside-down. Cups with water are often in a different schema – the water frequently spills from overturned cups – while the toy cat rarely falls from an overturned basket in this scenario. With the rollercoaster scenario “carrying” would be a less relevant p-prim – “guiding” as a p-prim would be more applicable (and, indeed, has been identified as the p-prim used in explaining the motion of a train on its tracks).

Multiple analogies

As the conversation continues, students in this classroom present multiple analogies relating to the toy cat in the basket to a bucket of water, tossing Halloween candy, throwing a hat with dice inside, and a basket of Easter candy (transcript 2, lines 137, 181, 184, and 201). Not all of the students that introduce these analogies agree with Miranda that the water will stay in the cup – however, they are able to understand the schema that Miranda has identified and are able to identify other members of the categories constructed by this schema – ones, perhaps, more prototypical for them and more obvious members of a category associated with the “carrying” p-prim (the dice are *carried* by the hat and the water *carried* by the bucket). In this way, the above listing of analogies can be seen as "fleshing out" the category in order to better categorize the novel water-cup system.

A recategorization of the target

A final claim I would like to make regarding this transcript is that the students are *re*categorizing the cup/water with the analogies they generate – an idea first introduced in chapter 4 and revisited here for the ontological and theoretical aspects of this claim. This requires that the cup/water was originally an element in a different schema, and the role of the analogy is not merely to map a new schema onto this existing problem, but to change the schema in which it is understood and defined. Why is this distinction important? First, it acknowledges that we understand and categorize objects and phenomena by an identification with a schema that we have in mind and that it is impossible *not* to do this: this is just how the mind works. If structure-mapping is this, the identification of a schema to apply to a given scenario, then, as noted above, *everything* is structure-mapping and it is not a reasonable account of analogy as distinct from routine similarity and categorization. Second, it acknowledges that the *schema* (or structure or p-prim) is primary: we schematize and categorize without awareness or careful consideration, but automatically.

If schemas are primary, it makes sense to think of the base of an analogy as representing a member of a category that the schema defines and not the other way around. That is, we do not move from the particular to the abstract when generating an analogy (though this may be a more reasonable idea in interpreting an analogy). We search for an analogy to explain, concretize and help us understand a schema we have already identified. Third, we only search for this analogy when the schema is at odds with a more expected schema – if the schema is expected, as with water spilling from a cup, it is often so obvious as to be invisible. (One can imagine that most students in the class are at a loss as to what to explain when asked what they think will happen to the overturned cup of water.)

This is consistent with diSessa's (1993) set of heuristics for identifying p-prims. Foremost among these is the "principle of obviousness." As diSessa state (p 121):

> The familiarity and unproblematic nature of some physical events needs explanation. In the present context, this usually means they need a p-prim to attach to them. In general, p-prims establish abstract classes of unproblematic happenings. This is the opposite of misconceptions research strategy, which never analyzes "correct" intuitions. The principle of obviousness gains explanatory power in conjunction with the principle of invariance; having understood p-prims underlying common events, we may be able to understand subjects' reactions to uncommon events using those same p-prims.

Just as misconceptions research does not analyze "correct" intuitions, neither does most analogy research, in particular structure-mapping, address the incredible ubiquity of "structure mapping" in everyday occurrences that we do *not* consider to be analogy. There is an obvious and expected answer to "what will happen to the water when you drop the cup." Most students assume that the water will spill and splash – that they do not explain this further is evidence that a p-prim is at play, in that it seems "obvious" and "impenetrable." Even Miranda, who predicts the water will stay in the cup, expresses surprise and fascination when the experiment is performed and the water stays in. Indeed, even to a trained physicist the result is eye-catching. But the brain has a way of understanding this, has a schema in place for this, and the role of the analogy is to identify an alternative schema and place this cup of water in a category associated with that schema.

The Beanbag Analogies

The analogies presented in this section were introduced in the last chapter for the phenomenological property that the base of the analogies are often constructed or invented, rather than recalled. Here I argue that the three students each are operating under three different schemas. As such, the analogies they choose differ and are prototypical of the schema they are employing. In the following transcript from a third grade class, the teacher has told the students that she is going to run while holding a beanbag that she wants to drop onto an "X" marked on the classroom floor. Should she drop the beanbag before, when, or after she reaches the "X"? Adam, one of the first students to speak, addresses Newton's Laws. The teacher (Trisha Kagey) asks for explanation. The following statements incite multiple spontaneous analogies, comparing the beanbag to a bike, a bat, a leaf, a rock and a feather (transcript 3, lines 35 – 40, 55 – 73, 83 – 87, 154 – 159 and 188 – 190):

Adam: … if you're riding your bike, um – it's in motion. And you're going to keep going until you get stopped by like – um, a rock or something – or going uphill…

Connor: I would think the bean bag would – might fall *behind* where you want it to fall because when I put – when I played baseball – they always said don't throw the bat because it might hit the catcher and not one of the um person because we're using metal bats, and – so we drop it, you drop it and then you – . Well, when I drop it, it usually swings backwards; it wouldn't be behind the plate instead of the front of the plate…
Teacher: Why do you think it fell behind?
Connor: Well actually it didn't mostly. It got on the side or in front because – well because you're supposed to drop it because you don't need a bat while you're running the bases. Once you drop it, I'm just

thinking also, what Adam is – well a bus – well if you were on a bus and you had uh, this little leaf that you found, and the window was open, and you drop it, it will go – it'll be going backwards…

Lauren: Because I think that's cause – you're talking about a leaf that's falling? That's because the – it's sort of – the bus is going back, so it's making like the air move. And the leaves are really, really light, so the reason they are going backward is because – Um, well it's going so fast…

Connor: What if you did it with a rock? The same thing will probably happen with a rock. Because you are probably like a bus, that you make the air come …

Kamran: … A rock is different, a rock has – it's also like, it's solid, but it's not that a leaf isn't solid, or a feather isn't solid. A feather – but you have to – it's very small, and it's very like thin, so you kind of say like solid. But anything hollow, like if you have a paper box…

Kamran: Yeah, because the weight pulls it right down. If a tree – it's heavy, and it's heavier than all the leaves it has, so the leaves will make it fly – fly here. And the tree, it will just go down.

In this segment, the beanbag drop is compared to a bike, a baseball bat, a leaf and a rock. The person doing the running drop is compared to the bike, the bus and a person. These items are not chosen arbitrarily, but because of a particular schema the students have.

Schema 1: A Newtonian Schema

Before discussing his analogy, Adam says "it will instead of going straight down, it will go um – it will go in front because it's not stopped yet. But when it hits the ground, because there is friction on the ground – there is more friction on the ground than in the air it will get stopped and land somewhere around there (the X)." It is only after the teacher asks Adam to explain it more clearly ("like you're explaining it to a Kindergartener") that Adam, after some pause, comes up with his analogy. This schema, which is consistent with Newton's Laws (objects in motion stay in motion), is not one with many members that would be well known to a young student – when walking, swimming, or pushing something, for example, you naturally slow down. A prototype is *not* a category member that is necessarily seen frequently but one that is seen frequently *as a member of the category*. "People's perceptions of how frequently exemplars instantiate their category, rather than people's familiarity with exemplars, appears to be the measure of frequency that is most central to graded structure" (Barsalou 1987). The bike is an appropriate and, for a child, prototypical instance of this schema, as it tends to keep rolling when on a flat surface – unlike when walking or running.

Schema 2: Intrinsic Motion

The analogies introduced by Connor and Kamran are rooted in a schema different from Adam's and more consistent with a phenomenological primitive. First consider the evolution of Connor's analogies. Connor jumps from analogy to analogy – first the baseball bat, which he discards when he analyzes it further, then the bus with a leaf, which evolves to the bus with a rock when he is pressed by Lauren. These are chosen because he believes that you will need to release the bean-bag *after* passing the X. This belief is evidence of a schema in which dropped items will be pushed backwards – and he is able to invoke two analogies as evidence. The prototypicality of these will be discussed in further detail in the next section, but a brief sketch is provided here. When switching to the bus analogy, there is no reason for the bus with a rock to be any more salient and immediate an analogy than the bus with a leaf unless Connor has a schema in mind already: one involving the "wind" pushing the object back, in which case a leaf is much more prototypical in this scenario than a rock, even though the rock has features (heaviness and irregular shape) that would make it much closer to the beanbag. Lauren picks up on Connor's selection of analogy as representing a category to which the keys would not belong, as they are heavy, and a person would not belong, as people are slower than buses. She suggests that "the leaves are really, really light, so the reason they are going backward is because, um, well it's going so fast – a bus is like going so fast that it's probably making the air go that way." Only then does Connor move his analogy "closer" to the beanbag by posing the question "what if you did it with a rock?" It is Kamran who identifies the two categories that are invoked by these students' schemas. I would like to suggest that the students are employing the p-prim of "intrinsic or spontaneous motion" (diSessa 1993), which has a schematization of "especially heavy or large things resist motion." Such a p-prim creates a dichotomy of objects that do and objects that don't resist motion (Adam's schema of "an object in motion will stay in motion" has no such dichotomy in Newtonian physics, but in "real world" physics there seem to be objects that obey this law and ones that don't). Kamran, a particularly vocal student who seems to voice his thought process, grapples with the categories that have been invoked by Connor's analogies: he wants to say that the rock and the leaf belong to different classes of objects, and yet he knows that they are both solids.

An illuminating comment is made when Kamran states that "a rock is different… but it's not that a leaf isn't solid, or a feather isn't solid." In this passage, we see Kamran negotiating the two categories that have been instantiated by Connor's schema, trying to match these categories with known categories (solids) but coming up empty: "A rock is different, a rock has – it's also like, it's solid, but it's not that a leaf isn't solid, or a feather isn't solid." He struggles to identify the ways in which these items could belong in different categories by identifying multiple members of those categories: a feather and a paper box as belonging to the category for which leaves are a prototype. But again he is stumped by the tree – "heavier than all the leaves it has" – as an object in the category for which the rock is prototypical, yet constructed of items for which the feather is prototpyical[2]. Kamran, because of his transparent thought process, demonstrates that these analogies are clearly defining certain categories and the task the students have is to determine to which category the keys belong.

The choice of base in these analogies is discussed in the following section, in which I address prototypes of "composite" categories, such as things that you drop and items from which you drop them (running and bats, buses and rocks, etc).

<u>*Styrofoam and ice-skating*</u>

The following set of analogies is taken from an undergraduate physics course. This course is a laboratory based conceptual physics course at the University of Maryland in which the students have no textbook and work in small groups and as a class to understand physical phenomena. In the following transcript, the students have worked in small groups, discussing the differences between what it's like for a charge in metal versus Styrofoam, and are now reporting and discussing their conclusions. The following analogies were drawn below were presented for their evidence of multiple analogies. I return to these here and identify the role that schemas play, and the reschematization that the analogies perform (transcript 1, lines 1 – 107). These analogies are assertions of categorization, and hence derivative of a schema, the base a prototype of the categories

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[2] An alternative interpretation of this statement is that the tree shows how weight is the significant factor – "It has leaves that want to make it fly, but it doesn't because the tree is so heavy."

defined within and organized by that schema, and multiple analogies as a way of negotiating that category.

Schemas

For a person, motion through something dense – a dense crowd, say, or a densely furnished room – is usually difficult. Motion is generally easiest in a medium that is not very dense. No one addresses this explicitly with analogy, again indicative of what diSessa has called the "principle of obviousness." However, students have noticed that charges appear to move easily in metals and are somehow "stuck" in the less dense Styrofoam and recognize the paradox.

This paradox demands that one categorize the motion of charges in a way that violates some expectations regarding motion. As such, it requires explanation and students are able to identify a schema in which this is not a paradox. By setting up an analogy the students are able to recategorize the metal and Styrofoam in a way consistent with schemas already at their disposal. Initially Christie suggests that the metal must be less dense – but, I contend, what Christie means by suggesting that metal is less dense than Styrofoam is that in a metal the motion of charges is easy, and so the metal belongs to a class of objects that allow for motion – a class often typified by low-density places. Lea's analogy identifies a case in which density enables rather than inhibits movement: ice-skating.

Multiple Analogies

In the above section, the phenomenological primitive of "intrinsic or spontaneous motion" (diSessa 1993) has a schematization of "especially heavy or large things resist motion" that establishes two categories (things that resist motion and things that do not).

Similarly, the schema of density enabling motion creates two categories: items that are dense enough to enable motion and items that are too not-dense and prohibit motion. The instructor, identifying this second category in this schema, finds a prototype: the sponge. Though not dense, it will not allow water to pass through easily. And Lea mentions water on a countertop and then the instructor makes an analogy to stepping-stones – analogies which, when viewed as an assertion of categorization, identify more members of the category typified by ice-skating.

Prototypicality

Claims of prototypicality are difficult to make: without doing an explicit study of the graded structure of the ad hoc category "media whose density enables motion," determining the prototypicality of a statement can only be inferred. However, some principles of prototypes can aid us in determining or arguing for the prototypicality of a particular base of an analogy. Rosch (1976) reports that

> prototypes appear to be just those members of a category which most reflect the redundancy structure of the category as a whole. Categories form to maximize the information rich clusters of attributes in the environment and, thus, the cue validity of the attributes of categories. Prototypes of categories appear to form in such a manner as to maximize the clusters and cue validity within categories.

For this reason, the prototypical bird would be one that is small, has feathers and wings and can fly. But defining prototypicality in a category that is not taxonomic, but instead one that is either goal based (as "foods to eat on a diet" for example) or otherwise ad hoc, such as "a medium for which density enables mobility," is difficult. Though ad hoc categories have a graded structure, "there appears to be a large class of determinants that is impossible to specify completely and that depends to some extent on the category and on the context in which it is perceived" (Barsalou, 1987 p. 104). Factors determining the graded structure include:

- Central tendency – for example, the features of birds mentioned above.
- Similarity to ideals associated with that category "where ideals are properties that exemplars should have if they are to best serve goals associated with their category." (Barsalou, 1987 p 105) For example, low-calorie foods for the category of things to eat when on a diet.
- How frequently it is perceived as instantiating its category. "People's perceptions of how frequently exemplars instantiate their category, rather than people's familiarity with exemplars, appears to be the measure of frequency that is most central to graded structure." (Barsalou 1987)

And yet these arguments still beg the question: why is a leaf falling from a bus (Analogy II) prototypical? Surely this scenario is infrequently, if ever, perceived. And what is meant by "central tendency" is difficult to ascertain in a relatively composite category for, as noted by Lakoff (1987 b "Cognitive Models and Prototype Theory"), a good example of a striped apple is neither a good example of striped things nor a good example of apples, and a small galaxy is not the intersection of prototypically small things and galaxies. Similarly, "things that fall behind you when dropped" is not the intersection of things that you drop and things that fall at an angle, while ice is not a good example of dense media and skating is not prototypical of motion.

To explain these as prototypes for the categories they instantiate, the claim of "similarity to ideals associated with that category" is more informative. However, *defining* those ideals requires an appeal to idealized cognitive models, schemas and p-prims. In particular, I argue that the schemas that are being employed in the bus-leaf analogy and the ice-skating analogy are built from multiple p-prims. These p-prims are put together in a larger composite schema that is then concretized by the base of the analogy. The prototype structure – the fact that something is identified most quickly and is a better exemplar of the category – need not imply that the prototype is a permanent fixture stored in memory as a representation of a schema, but rather that, under these circumstances and in this set of activated schemas, this particular representation of the schema is accessed most easily.

Miranda's analogy hinged on a single p-prim (namely carrying), but her selection for the base of her analogy arose from this schema (carrying) together with the upside-down property of the cup and even, perhaps, the idea that "something weird" would happen. The analogies presented in the past two transcripts are also based on phenomena more complex than a single p-prim. Consider the schema that Connor may have: I posit that Connor has two stories or schemas that this beanbag-running-drop invokes: one is simply the schema of running and dropping something, for which baseball and the bat is quite prototypical and is tied to a second schema of what happens after that drop occurs. This second schema is something like "things in motion are pushed backwards by the wind." This schema, contrary to Adam's schema of "things in motion stay in motion until stopped," may entail the p-prims (all quotations from diSessa 1993) "intrinsic or spontaneous resistance" (with a schematization of "especially heavy or large things resist motion"), and "force as mover" (here the "wind" force moving the leaf). Such a schema would explain why Connor rejects his initial analogy (it is derivative of a different schema than addresses the question at hand, namely things that you drop as you run) and explains his choice of objects for the second analogy he chooses. The leaf is prototypical – readily activated within this schema – in that it is consistently a member of object that are affected by wind, *and* the bus is prototypical in that it consistently creates this "wind" force (or, as Lauren says, "well it's going so fast – a bus is like going so fast that it's probably making the air go that way") and is an object with which students are quite familiar.

The analogies surrounding the motion of a charged particle in metal (an aluminum pie plate) hinge on the idea that density is in some way enabling motion. One implication from the initial analogies (ice skating, a countertop and a sponge) suggest to one student that the charges are moving across the top of the metal (transcript 1, lines 83 – 86), which she finds problematic because charges should be throughout the metal ("it's made up of it"):

> Anna: So you're saying the charge is like on top of the metal? Like on the outside?
> Lea: Yes.
> Anna: It's like made up of it – like, they're electrons.

Lydia agrees with the student above and suggests that the electrons, instead of "skating" across the solid metal, are hopping from one molecule to the next. Paul then concretizes the schema, selecting an analogy to stepping-stones (transcript 1, lines 113 – 121):

> Lydia: I was going to say I think the pie plate is more dense but I do think that it's inside not outside because if there's more space to travel then the molecules can't get from one space to another easily but it's all [inaudible].
> Instructor: Oh so it's like stepping stones [Lydia: Kind of.] like in the Styrofoam it's really far to the next stepping stone so it's like can't get there I'm stuck here. [Lydia: Right] but in the metal the stones are really close together so I can kind of walk across. [Lydia: Yeah.]

The base of the analogy comes *from* the schema, and – just as happens in the beanbag analogies – as that schema changes, so do the analogies.

<u>*Analogies regarding a quantum mechanics problem*</u>

The following transcript, presented in the previous chapter, follows two undergraduate physics majors working on a homework assignment on angular momentum in quantum mechanics. The students have had instruction on how to arrive at the quantum numbers *S* and *L* but are asked to find the square of the total angular momentum, $(\boldsymbol{J})^2$, which is $(\boldsymbol{S} + \boldsymbol{L})^2$, or $(\boldsymbol{S})^2 + 2(\boldsymbol{S} \cdot \boldsymbol{L}) + (\boldsymbol{L})^2$. The students know how to find $(\boldsymbol{S})^2$ and $(\boldsymbol{L})^2$ but not $2(\boldsymbol{S} \cdot \boldsymbol{L})$. They have a solution set from another student that provides the answer but not the steps to arrive at that answer. There are two analogies presented in the transcript, both an expression of the kind of problem they are solving: how to approach the problem and how to understand the quantities in the problem. The first (transcript 5, Lines 10 – 27):

> Anselm: ’Cause you’re assuming that if you have the example, suppose there’s a charge here, what’s the electric field due to it? You can figure out, suppose you have Bugs Bunny, and he’s charged, what’s the electric field around his ears? All right. Because you have a simple example when they’re both the same, you’re not going to be able to figure out exactly what you’re supposed to do when the rules weren’t the same. Cause now it’s fixed.

And then, (transcript 5, lines 64 – 80):

> Ben: But you’re mixing apples and oranges. It’s dumb!
> Anselm: Yeah that’s so messed up, yeah that’s not the answer. If I just ignore the fact that I’m in the three-halves one-half and I’m in the one-half one-half and I just add them all together,
> Ben: I once had a professor tell me that um, well if you got the right answer, you certainly know how to do the problem. I had to convince him no sir, you can jiggle these numbers any way you want. And come up with the right answer if you know the right

> answer in advance. Of course we're not sure that this is the right answer.

Reschematization of the base

What kind of analogies should one expect in discussions of quantum mechanics? What schemas are available to understand this branch of physics that has no obvious analogs? In this discussion between two students, their analogies are with respect to mathematics and problem-solving strategies, not concerning the nature of quantum mechanics. While this transcript is not long enough to draw any meaningful information regarding analogies in quantum mechanics, it is interesting to note that the schemas introduced here are not regarding wavefunctions or expectation values, but instead related to problem solving and epistemology.

The first analogy is a response by Anselm to Ben's claim "We should be able to figure this out from today's lecture." Ben believes they should be able to solve the problem with information from the day's lecture on simple quantum numbers. Anselm offers an analogous case and then provides the abstract schema from which that case was derived: "Suppose you have Bugs Bunny, and he's charged, what's the electric field around his ears? All right. Because you have a simple example when they're both the same, you're not going to be able to figure out exactly what you're supposed to do when the rules weren't the same." It is clear that Anselm's analogy is a reschematization – this problem is not one that can be solved from simple principles but requires more sophisticated tools.

The second analogy is, again, a reschematization. The students know what the correct numerical answer is and are trying different combinations of numbers in the problem to arrive at that answer. When dealing with numbers in many (if not most) mathematics courses, there are rarely rules about which numbers can be combined and in what order. In situations when numbers have physical meaning – as in this physics problem – there are rules about what kinds of numbers may be added and in what way. These rules have been temporarily ignored to find a pattern by which the students may arrive at the correct answer, but when the answer is arrived at, Ben notes the need to reschematize the problem from one of combining numbers without physical meaning to recognizing the meaning (or lack thereof) behind the math, claiming: "But you're mixing apples and oranges. It's dumb!" He then tells a story (in what could be interpreted to be a multiple analogy) that relates this idea again and reiterates the reschematization – beginning with the professor's claim that "if you got the right answer, you certainly know how to do the problem" and then contrasting that with the story: "you can jiggle these numbers any way you want. And come up with the right answer if you know the right answer in advance." In telling the story he tells the more abstract schemas that apply. And again, each schema is locally coherent – it is a routine that makes sense in a limited set of problems.

The ontology of authenticity

Reschematization of the base

This analogy, from a Physics Education Research Group research meeting, was presented previously for the chain of analogies it presents. The meeting is being run by Paul who is trying out a definition of "authentic" in the context of classroom activities. He has chosen to define authenticity as not only a property of the activity, but also relating to the students' interaction with that activity and the (science) community of practice's judgment of the activity. (For example, how would the students characterize the reason for what they're doing? Would scientists agree with that reason?) Not only is this is at odds with common definitions of "authentic" curricula as a property of the curriculum itself, but it is contrary to a cognitive model of attributes in which a property is a property *of* something: defined relatively objectively and inherent to that something. Most adjectives or properties belong to this kind of ontology: if I claim that a car is fast, red, and Japanese, for example, there is an objective measure of the truth of that claim that is independent of culture, personality, or me. Anyone else looking at that car will agree that it is fast, red and Japanese. If I have an authentic pearl earring, authentic is used in the same way: an objective measure and a property of the pearl, independent of context. Rachel asserts an analogy to make explicit claims on the ontology of authenticity: ontologically, authenticity is *not* like fast, red or Japanese. She finds an attribute (fun) that is easily understood as not being inherent in an activity. (Transcript 3, lines 9 – 29).

There is an entire story, or schema or cognitive model, associated with "fun," and "fun" occupies a role in this story. Similarly, authenticity, Paul argues, has a similar story and occupies the same role in that story. This "role" is a category – one generated by the schema. However, there is a fundamental difference between the story that you tell for "fun" and that Paul is trying to tell about "authenticity" – there is a community of practice argument. Leslie (I) introduces this question – *first* identifying the schema and *then* moving towards finding the analogy (transcript 3, lines 38 – 79).

Rachel prefaces her analogy by claiming that the analogy will be one of ontology. The "work" that this analogy does for the group is to say: what you're doing with authenticity is not new – we have a way of thinking about this. You (Paul) are placing "authenticity" into an existing ontology – one that is characterized by "fun." Leslie's (my) concern was that the ontology was not entirely consistent with Paul's definition. Whereas the "fun" of an activity can be determined solely by the person doing the activity, Paul relates authenticity to a community of practice – so that a scientific community must agree with the student's judgment of an activity. Attempts to "patch" the analogy by considering "good, clean fun" instead of just "fun" are an attempt to change the ontology of that base. "Worship" was chosen by Leslie because of its relationship to both an individual and a community.

Conclusion

How is a concept represented in memory? Is it represented by the *kind* of knowledge it is? The way that you find its solution? By the ontology of the items in the concept? Is there a stable representation of "apples" as "the thing that can't be compared to oranges?" A representation of Bugs Bunny as "a strange shape for which the electric field would be difficult to construct?" Is money represented as currency or wealth? If we ascribe to concepts a particular representation in memory, then Bugs Bunny would have to have such an attribute (or, at the very least, would have to be connected to these ideas) and Marc and Vic would have to have different concepts of the ontology of money. Theories of analogy that attribute stable representations to concepts must account for the overwhelming number of features that are part of the representation of a concept.

As mentioned previously, to account for the nature of categories, in particular their graded structure, Lakoff (1987) has proposed that categories are defined *within* particular idealized cognitive models (ICMs) of how the world works. It is only within a particular ICM (or schema) that a category is meaningful, and these categories become les meaningful and exhibit a graded structure to the degree that the schema in which they are defined does not apply. Categories, then, arise from schemas which are activated or not, applicable or not, depending on context. Because of the variety of schemas and the variety of ways they may be combined, categories can have a flexible structure, and members of categories can shift their membership. Categories need not have a fixed representation, but arise from the particular schemas and resources that are activated by the context.

As an alternative to structure-mapping and other theories of analogies that require unitary representations of concepts, I posit that analogies are assertions of categorization. Instead of "preexisting metaphorical mappings" (Gibbs, 1992) analogies instantiate preexisting schemas and their associated categories. Categorization does not require that there be stored representations of concepts or categories, but that "concepts originate in a highly flexible process that retrieves generic and episodic information from long-term memory to construct temporary constructs in working memory" (Barsalou 1987).

Chapter 6: Analogies in the History of Science

Introduction

The past two chapters are the bulk of the dissertation – starting with the properties of generated analogies in science (that is, the phenomenology) and then addressing an ontology of mind to account for these properties. In this chapter, I introduce the ways in which analogies have historically been used in science and explore the consistency between analogies in science and the model of analogies introduced in the previous chapters. These analogies are detailed in works of comparative literature, popularized science, cognitive science and the history of science. I begin with analogies from physics and how the role of physical analogy – namely Maxwell's analogy between magnetism and gears – is understood in the philosophy of science. Then I turn to biology and the idea that the theories introduced by science are often brought about by the recognition or activation of a schema. That is, identifying and projecting schemas – one important part of analogy – is how science happens. However, schema projection is not the whole story – often the projection of a schema is implicit, and it is the deliberate use of a contradictory schema that I define to be analogy. I then consider the deliberate use of analogy and the ways in which this has come to be understood by historians of science and cognitive scientists.

In *Metaphors We Live By* (1980) Lakoff and Johnson argue that metaphors structure our thoughts and influence our conceptions of the world, and that the role of metaphor in scientific thinking provides one of the best illustrations of this principle:

"Formal scientific theories are attempts to consistently extend a set of ontological and structural metaphors." This claim that scientific theories are extensions of the metaphors that we employ in other areas is nothing new. In the 1850's, with the development of the telegraph and its influence on theories of the nervous system, many scientists recognized, and at least one scientist argued against, the epistemological value of analogy in science. As noted by Laura Otis (2002), Claude Bernard (1858) criticized the analogy between nerves and the telegraph, claiming, "people's 'knowledge' of the nervous system had consisted largely of a series of comparisons, 'the expression of a way of seeing meant to explain the facts.' Priding himself on his empiricism, Bernard mistrusted analogy as a means of constructing knowledge." This concern – that analogies (a "way of seeing") masquerade as understanding ("explain the facts") – was echoed in a cognitive science course at the University of Maryland. The professor noted that cognitive scientists have employed the idea of "outshining" to explain phenomena in which stimuli we usually attend to are ignored in the presence of other stimuli, analogous to the way in which the sun "outshines" the stars during the day. Star's light is not weakened by the sun's light but "outshone" so that they are not seen. Outshining in the solar sense, he argued, has an understood mechanism, while outshining in the cognitive science sense cannot realistically have the same mechanism, but no mechanism is proposed. In this case, the analogy masks the lack of understanding. What is missing from this analogy? What role does "outshining" serve? Why mention it at all if it does not contribute to the understanding? What, exactly, is the epistemological value of analogy?

First, I have argued, the importance of an analogy is its assertion of an unexpected categorization, meaning that you are identifying an alternative cognitive model for this scenario. In the case of “outshining,” the analogy functions, as all analogies do, to reschematize the phenomenon. For outshining, the reschematization is changing the cognitive model from one in which stimuli are responded to on the basis of their absolute value, and instead responded to only by their relative value. Such analogies in science, because they are an assertion of categorization, and therefore shift the cognitive model applied in understanding the target, is what Koestler has identified as the “essence of creativity:” being able to view a situation or an object from two different frames of reference, or two ‘unrelated matrices of thought’ (Koestler, 1964). Or, as Chi (1997) states, “the essence of creativity is… re-representing an entity or a situation from one ‘ontological’ tree of concepts and categories to another ontological tree of concepts and categories.” (Although I differ from Chi in the robustness and structure of those “trees” – these activated schemas may be put together in a wholly new way to understand the new phenomenon.)

Second, re-categorizing the target of the analogy is extremely powerful: not just because of the inferences one may draw, but because it affords one a new language. Once the target is understood through the lens of a different (and possibly more appropriate) cognitive model, the target may now be referred to using the language and categories defined within the new cognitive model. It is within this new framework that a structure-mapping process may take place to construct a mechanism – a crucial and necessary step for employing the analogy – but the primary role of analogy is the entrance into that cognitive model – to “tie it down” in a concrete way – and access to a new language with new categories. This new framework is similar to what Otis (2002) refers to as a new image (her use of the term “image” is not in the sense of image-schema or image-representation):

> Metaphors provoke and give birth to new images. By establishing and reinforcing connections, they encourage us to see in new ways. While Bernard is correct that assertions of likeness alter the way we see, Lakoff and Johnson are equally correct in claiming that “much of cultural change arises from the introduction of new metaphorical concepts and the loss of old ones.” Alterations in the way we see can be extremely productive.

Because of this process of theory building via analogy, our scientific theories are often an extension of the stories that our lives tell: through our political systems, technology, and experiences.

This chapter is not intended to be an in-depth analysis of the evolution of theories in the history of science. Instead I draw from the work of others regarding the history of science and explore the consistency between their ideas and my definition of analogy. I will explain how several theories that are clearly based in analogy and detailed in comparative literature (Otis, discussing Ramón y Cajal), popularized science (Burr, writing about Turin), cognitive science (Gentner on Kepler), and the history of science (Nersessian on Maxwell) are consistent with a category framework of analogy. This is not to say that all scientific theories evolve via analogy to known systems; rather, I claim that the process of analogy is prevalent in the scientific community and the manner in which analogies are used is consistent with a categorization framework.

History and Philosophy of Science

I begin with examples in the history and philosophy of science from physics. As noted in the first chapter, it is not hard to find instances of analogy in the creation of theories in physics. Einstein, who had a background in physics, was working as a patent clerk in Switzerland during an era of train travel (Galison, 2003). A great deal of patents at that time involved synchronizing clocks from one station to the next – and Einstein's special theory of relativity was often described (by Einstein and others) as a question of synchronizing clocks on a train. Kosterlitz and Thouless (1973) drew an analogy between order parameters and their associated phases on the one hand and topology on the other. Nancy Nersessian, a philosopher of science, has studied what is referred to as "the method of physical analogy." She studies model-based reasoning, such as the type employed by Maxwell in determining the electromagnetic field equations. Maxwell constructed a model of electromagnetism in materials that consisted of vorticies that created a series of interlocking gears – "idle gears."

Nersessian has developed a hypothesis regarding the manner in which mental-modeling works and how it is employed by scientists. Her mental-modeling hypothesis is that

> In certain problem-solving tasks humans reason by constructing an internal iconic model of the situations, events, and processes that in dynamic cases can be manipulated through simulation. In constructing a model, information in various formats, including linguistic, formulaic, and imagistic, where the latter is taken here to include various perceptual modalities, can be used.

A question that is often asked of model-based reasoning is that, given that the model is an existing and understood model, how can model-based reasoning "be generative of conceptual change in science?" To this Nersessian responds that it "requires a fundamental revision of the understanding of concepts, conceptual structures, conceptual change, and reasoning." To address this concern, Nersessian argues, we must revise the notion of a concept:

> A basic ingredient of the revision is to view the representation of a concept as providing sets of constraints for generating members of classes of models. Concept formation and change is a process of generating new, and modifying existing, constraints. This is accomplished through iteratively constructing models embodying specific constraints until a model of the *same type* with respect to the salient constraints of the phenomena under investigation, the ‘target’ phenomena, is achieved. (Nersessian, 2002, p 139)

I would like to stress from this the claim that the representation of a concept is a set of constraints for generating *new members of classes of models*. The set of constraints is identified by finding analogous cases (in the case of Nersessian’s studies, these analogous cases are models) and a case is deemed analogous by being one of the “same type with respect to the salient constraints of the phenomena.” Mental-models, then, which are prevalent in the development of scientific theories, operate by being members of a class – a prototype of a category, I argue – that are useful for their ability to determine the set of constraints necessary for the representation of a concept. Though the final negotiation of the set of constraints may be a structure-mapping process between the particular base of the analogy (or model in the method of physical analogy), the primary role of analogy – the assertion made when the analogy first is introduced – is one of categorization[1]. Again, the categorization is indicative of a particular cognitive model and that model creates a language for discussing the concept. This differs from structure-mapping theories of analogy in that the significance is not tied to the base *in particular* except for its role in being a prototype for a category invoked by a common schema. Nersessian (2002, p. 138) writes,

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[1] Another possible interpretation, which I will not go into in detail here, is that this category is a wholly new category that represents a “blended space” as detailed by Fauconnier and Turner (1994). This idea will be explored in the conclusion as a possible direction for further research.

> In model-based reasoning processes, a central objective is to create a model that is of the *same kind* with respect to salient dimensions of the target phenomena one is trying to represent. Thus, although an instance of a model is specific, inferences made with it in a reasoning process are generic. In viewing a model generically, one takes it as representing features, such as structure and behaviors, common to members of a class of phenomena. The relation between the generic model and the specific instantiation is similar to the type-token distinction used in logic. Generality in representation is achieved by interpreting the components of the representation as referring to object, property, relation, or behavior types rather than tokens of these. One cannot draw or imagine a "triangle in general" but only some specific instance of a triangle… In considering the behavior of a physical system such as a spring, again one often draws or imagines a specific representation… *That is, the reasoning context demands that the interpretation of the specific spring be generic."*

The point that I take from this for my thesis is that the base of an analogy is more abstract than a particular analogy appears. Maxwell's analogies of idle gears was no more tied to that particular representation of idle gears than claiming two ideas are "apples and oranges" is tied to any particular instance of comparing apples and oranges. It is simply a prototypical instance of a class of phenomena that share a place within a certain cognitive model. Similarly, Miranda's analogy to the toy cat was only one salient example of the story (or cognitive model or phenomenological primitive) of carrying. The base of the analogy refers to a category – "one takes it as representing features, such as structure and behaviors, *common to members of a class of phenomena*" (emphasis added). And the base in particular is chosen only because we cannot imagine categories in general or reason about them generically but must choose a single representation to reason with. This representation is what researchers in categorization have termed the category prototype.

Comparative Literature

I now turn from physics to biology: first findings from comparative literature and then a reiteration of these findings from studies on scent. The following ideas from comparative literature are by a professor who has a background in biology. The idea that her findings underscore is that our science evolves from the cognitive models that we have in mind, as provided by our culture and technology.

Membranes

Otis (1999), a professor of comparative literature, was pursuing the concept of identity as scientist-authors in the 1800's defined it. In particular, she explored how "the changing understandings of personal and national identity encouraged people of the 1830's to see living things as associations of independent units" (Otis, 2001). Both the political climate of colonialism and the scientific studies of cells created the ideas of entities with porous but definite membrane borders. In her work *Membranes* (Otis, 1999), she writes:

> In their respective languages, all of these physician-authors confront their cultures' demands for borders, and they express and challenge them through common metaphors and maneuvers. This coincidence suggests that imperialistic culture, which offers the same metaphors to scientists and novelists, shapes both biology and literature by shaping the language through which they express themselves… the relationship between literature and science is one of mutual feedback and suggestibilty, each contributing to and drawing up on the "cultural medium' out of which it grows. Culture, however, does not "determine" science or literature any more than science and literature determine culture: personal vision persists, despite all indoctrination and all scientific training. (p. 3)

One particularly illuminating story that Otis tells is that of Ramón y Cajal, the Nobel Prize winning biologist who determined that the nervous system is made of discrete cells and is not a continuous net-like structure, as it appears. She questions why this had not been determined before – Golgi had invented the necessary techniques years before Ramón y Cajal employed it in studies of nerves – and she questions "what was it, I wondered, that drove Ramón y Cajal to keep looking, determined to resolve boundaries between cells when there appeared to be no boundaries at all?" The answer, she determines, is that the cultural medium of the time was creating a particular vision:

> Many factors besides the essential technical ones affect what one sees under a microscope, or at least the way one describes it. It has been proposed, for instance, that late 18th-century German philosophy, with its stress on individual perception, inspired people in many fields to conceive of life in terms of independent living units (Rothfield, 97). How might politics and culture shaped cell theory?… Cell theory relies on the ability to perceive borders… Germ theory… encourages one to think in terms of 'inside' and 'outside.' If one believes that invisible germs, spread by human contact, can make one sick, one becomes more and more anxious about penetration and about any connection with other people – the same anxieties inspired by imperialism" (Otis 1999 p 5).

That is to say, the cultural medium in which science exists strongly influences the way in which data is seen: the existing stories the culture has constructed provide expectations for the data. Her study on the connection between national agenda, scientific theory and literature, compels Otis to claim that "the division between the humanities and the natural sciences [is] another boundary arbitrarily drawn. Scholars on both sides of the line want to answer the same questions, and we express ourselves through metaphors provided by a common culture." It is no secret, particularly within qualitative studies, that our culture biases our interpretation of data. What Otis demands that we recognize is that our culture influences our hard sciences as well as our art, and it does it in the *same way*. This echoes a comment by Robert Irwin, an abstract artist who was paired with a physicist in "cultural exchange" experiment. Initially both artist and scientist were pessimistic on the merits of this pairing, but quickly found that they were both addressing common questions with their work and found collaboration easy. Irwin, in his biography, comments:

> I really feel that there is a kind of dialog of immanence. That certain questions become demanding and potentially answerable at a certain point in time, and that everyone involved on a particular level of asking questions, whether he is a physicist or a philosopher or an artist, is essentially involved in the same questions. They are universal in that sense. And although we may use different methods to come at them, even different thought forms in terms of how we deal with them – and we will eventually use a different methodology in terms of how we innovate them – still, really those questions are happening at the same moment in time. So that when we find these so-called accidental interrelationships between art and science, I don't think they're accidental at all.
>
> -Robert Irwin

This "dialog of immanence" I believe is related to what Otis refers to as the "cultural medium." The "certain questions" that become demanding are those that our paradigms provide us. And those paradigms are not so local as Kuhn (1970) suggests in his *Structure of Scientific Revolutions* – they can be broad cultural paradigms. They are the cognitive models supplied by our daily experience in our culture. These models (stories or schemas) are responsible for our categories, which in turn allow us to *be* creative and reconceptualize our science, art, medicine, political systems and economies. If creativity is a shifting of categorization ("re-representing an entity or a situation from one 'ontological' tree of concepts and categories to another ontological tree of concepts and categories" Chi, 1997), and analogies are assertions of that unexpected categorization, then it is changes in our cultural medium[2] that provides us with the new categories,

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[2] It is not, of course, such a strong dichotomy: culture versus science. Art, technology and science are all contributing to the cultural climate. The point that Otis is making, though, is that these parts of culture are far more intertwined than previously thought. Culture, as defined by the political climate in particular, influences science – hard science – far more than one would think and the way it does it is by giving us new schemas and the new language associated with those.

derivative of new cognitive models, in the first place that allow us to be creative. These "accidental interrelationships" (Wechsler/Irwin), are not accidental at all, but are due to the "metaphors our culture provides us" (Otis, above). And these metaphors are not simply local structures that we map but are creating new ontologies, new categories, derivative of new cognitive models.

So far, this points to the following: we see – in our data and in our art – what we expect to see and those expectations come from the cognitive models we have developed from our experiences and our culture. We understand and categorize phenomena based on the cognitive models that we have in place. But this is only part of the story. For this still begs the question: *is this analogy*? Insofar as I have defined it, unless there is an explicit negative assertion, where the mind considers two possible schemas – each coherent within its own framework, but only one of which is possible – then this is not analogy. Ramón y Cajal's insistence on looking for membranes *may* be such an instance, but it is not clear from the story provided. It is doubtful that he understood his research in the larger cultural paradigm and deliberately chose a schema of boundaries over the continuum model.

Rather, this insistence on borders and boundaries in what are otherwise continuous, unbounded regions, sets up a particular resource and this resource is continually activated by the culture. It was, perhaps, never a deliberate cognitive "choice" to activate it. For a case that is more clearly one of analogy, consider the role of networks and the telegraph on understanding the nervous system.

Networks

Otis' first study, a study on identity, led her to a realization that the concept of membranes pervaded literature and science at a time when the political climate of imperialism demanded the idea of borders. In a second study, Otis (2001) explores the idea of communication and traces the idea of networks, again looking at the nervous system and its theoretical development as consistent with the telegraph. Just as McLuhan professed, "the medium is the message," so Otis (2001) finds that the message cannot be "abstracted from the medium that transmits it." In particular, the advent of electronic communication has forced a reconceptualization of our selves:

> Since the late 1840's, electronic communications networks have changed the way we see our bodies, our neighbors, and the world. For a century and a half, these networks have suggested webs, leading their users to think as though they were part of a net. Between 1845 and 1895, the development of the telegraph transformed people's understanding of communication and, with it, their notion of their relation to others. As the telegraph affected language, Carey argues, it 'changed the forms of social relations mediated by language' (Carey, James, 1989 p 210). The telegraph became 'a thing to think with,' shaping the thoughts that it wired. (Carey p 204)

In the seventeenth century it was thought that muscular motion, determined in the brain, was mediated by pressures in a nervous fluid. As Otis (2001, p. 14) notes: "observing the brain's ventricles filled with cerebrospinal fluid, the earliest anatomists envisioned the nerves as a kind of circulatory system, drawing inferences about their structure and function by comparing them to a system whose structure and function were more obvious." Though criticisms of this mechanism were made and scientists (namely Galvani) argued for replacing the hydraulic model of the nervous system with an electronic model, this alternative was not adopted until after the advent of the telegraph. As Lenoir (1993) argues, scientists' familiarity with electrical circuits affects "not just the way they performed their experiments but the way they conceived of the nervous system itself." That is, the technology allowed for a change in theory – and not because of the ability to make new measurements (telegraphs as a technology are not a tool for discovery in that sense), nor because of the change in theory regarding telegraphs (electricity was understood well enough to created the telegraph but was not applied to nerves until after the telegraph was invented), but because of a cognitive model that it afforded, allowing scientists to see and categorize phenomena that they had no way of understanding otherwise.

In this century, the nervous system is referred to "in the language of the cybernetic web" (Otis, 2001). Indeed, even the idea of where thought occurs has moved from the brain to this interconnected web in the paradigm of distributed cognition (Brown, Collins, and Duguid, 1989) – an idea that one could argue finds its origins in the transmission and growth of knowledge enabled by the internet. This relationship between technology and theory – in which technology is not only created by changing theories, but often vice versa – can offer an explanation for Robert Irwin's observation that artists and scientists seem to address questions that become "potentially answerable at a certain point in time." These questions arise because, as Otis claims, "the technological metaphors affected… decisions about which phenomena to study and what experiments to perform." (p 3) Not only because or technology affects what we can study, but what we choose to study and how we represent and understand our findings.

Some ideas seep into the consciousness of our culture – through our language and technology – so that we cannot help but use these ideas as a lens on other phenomena. Some ideas require an explicit cognitive work – it is a lens you must "put on" to see phenomena in a new way. With Ramón y Cajal's work on cell membranes, the lens was perhaps unconscious. But with the electrical properties of the nervous system the analogies were explicit (Dubois-Reymond, 1868 p 97):

> just as little telegraph wires, do the nerves betray by any external symptom that any or what news is speeding along them; and, like those wires, in order to be fit for service, they must be entire. But, unlike those wires, they do not, once cut, recover their conducting power when their ends are caused to meet again.

Again, this explicit use of analogy reiterates the manner in which certain implicit metaphors and categorization differ from deliberate analogy. Though many researchers place analogy on a continuum that includes rather mundane instances of similarity and categorization (Gentner and Markman,1997; Hofstadter, 2001), I claim (or more accurately *define*) that analogy differs from categorization and routine similarity in that analogy requires a reschematization of the target while categorization does not. In the following quote, Otis (2001) notes the problematic distinction between category and analogy:

> In his Foreward to Kittler's *Discourse Networks*, David E. Wellbery declares that 'in its nervous system, the body itself is a medial apparatus (xiv).' He means, of course, that the nervous system is *like* an electronic medium – or does he? If they perform the same functions, are nerves *like* cables or are they identical, members of the same functional category? Metaphors elide likeness, masking a key epistemological link. But what is the epistemological value of metaphor? What does one gain by saying that one thing is like another?… It could be objected that nerves are alive and thus inherently different from any sort of technological apparatus. Since the early nineteenth century, though, drawing a distinction between organic and technological systems has grown increasingly problematic.

In this paragraph, Otis notes that the claim of analogical likeness is not so far from the claim of category inclusion. The reason one may wish to say that nerves are "like" an electronic medium is because of nerves have this quality of being alive – and so couching this claim in analogy form ("nerves are *like* cables") recognizes that there is a violation of expected categorization: living things are not machines. But increasingly this distinction between organic and technological is problematic – as we begin to understand the human body in terms of machines, this idea may shift from an assertion of analogy (*shifting* the schematization of the concept) to more routine categorization (in which the "machine" category no longer differentiates living things from non-living things), in which someone may claim that the body *is* a medial apparatus – or even simply use the language of telegraphs to speak of the nervous system – without there being the tone of analogy present.

Below I present a more modern example of technology (the scanning electron microscope) influencing science by providing a schema by which we understand scent, and the way in which the previous understanding of scent had been a rather implicit application of a schema that, in terms of predictions and an understanding of olfaction, was not generative. I then return to theories in physics with an analysis of a historical analogy relating the sun's relationship to the motion of the planets to the sun's light.

Luca Turin: Analogies involving scent

The mystery of our sense of smell stems from the puzzling ability to smell everything instantaneously. In order to smell something, we take particles of it into our nose and these are detected by the olfactory system. However, as noted by Burr (2002), our other systems that detect particles that have come into our body, the digestive system and the immune system, have evolved so that they can either work instantaneously on a limited number of molecules (the digestive system) or can handle a myriad of molecules but take a significant amount of time (the immune system). This stems from the role of enzymes – the body either has enzymes on hand, perfectly manufactured to bond to the molecule or it must create the enzymes. The digestive system has evolved to have enzymes ready to digest a limited number of molecules and does so immediately, while the immune system has to make them – a powerful ability that enables us to fight off diseases that we have never in our evolutionary history seen before, but an ability that takes time, hence the difference in response times. The paradox of smell is that the olfactory system can smell a manmade molecule that has never been smelled before and can do so instantaneously. Perhaps unwittingly, prior to Turin's work on smell, scientists were assuming that smell worked according to the same principles as the digestive and immune systems – it is only because of this parallel that one should be surprised that the olfactory system can handle novel molecules instantaneously (had they assumed smell worked according to principles similar to sight, where we can see shapes we have never seen before, then this property of smell would not be surprising).

Turin's idea was that smell was not appropriately schematized – in a sense, the scientists were asking if the Pope is a bachelor. The questions they asked about the sense of smell were difficult to answer because they were not appropriate. Questions asked of enzymes, of shape and timing were not the right questions – they were questions provided from the schemas associated with the immune system and digestive system, a schema that does not fit the olfactory system – but with no alternative schema, these were the only questions available *to* ask. Just as the invention of the telegraph inspired theory of the nervous system, recent developments in microscopy in physics provided an analogy for Turin, a way of reschematizing smell. Turin proposed that smell works according to the same principles as a tunneling microscope: the molecule providing an electrical connection and the strength of that connection related information regarding the structure of the molecule. In this schema, the *shape* of the molecule is not important, enzymes do not factor into the process of smelling, and a question of how we can smell novel molecules instantaneously is not an issue. As with Otis's findings in membranes and networks, it was changes in technology that enabled changes in theory: *not* because the technology was a necessary element in discovery but because the technology created a new schema and allowed the reschematization of smell.

Cognitive Science

Gentner's (2002) structure mapping theory has been to understand developments in the history of science. In particular, she has looked at the analogies of Johannes Kepler. Kepler, born in the 1500's, inherited an astronomy of spheres in which planets circumnavigated the sun by the will of souls (later translated to angels or virtues or spirits). However, there were regularities and features in the data of the motions of the planets that required explanation. In seeking to understand why the planets that were further from the sun moved more slowly, he argued (Kepler, 1596, p199):

> …one of two conclusions must be reached: either the moving souls are weaker the further they are from the Sun; or, there is a single moving soul in the center of all the spheres, this is, in the Sun, and it impels each body more strongly in proportion to how near it is.

That is, the sun is responsible for the motion of the planets and the closer you are to the sun the more it can make you move – the sun is transmitting a motive power through space to the planets and this power is closer when one is closer to the sun. To make sense of this argument, he appealed to analogy:

> I shall propose to the reader the clearly authentic example of light, since it also makes its nest in the sun…Who, I ask, will say that light is something material? Nevertheless, it carries out its operations with respect to place, suffers alteration, is reflected and refracted, and assumes quantities so as to be dense or rare, and to

> be capable of being taken as a surface wherever it falls upon something illuminable. Now just as it is said in optics, that light does not exist in the intermediate space between the source and the illuminable, this is equally true of the motive power (Kepler, 1609/1992, p 383)

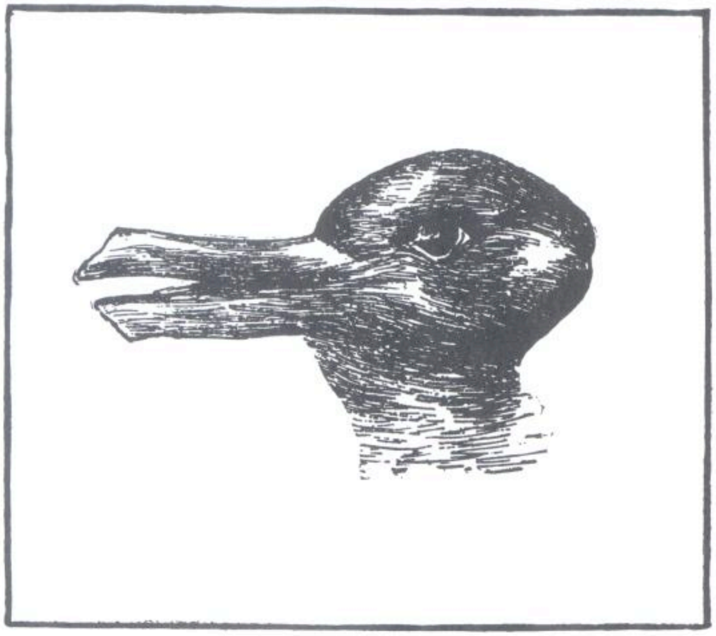
To understand the role that analogy plays for Kepler and "knowledge change" (p 28), Gentner (2002) argues that there are "at least six ways in which the process of analogical comparison can lead to knowledge change…

1. highlighting and schema abstraction – extracting common systems from representations…
2. projection of candidate inferences…
3. noticing alignable differences – becoming aware of contrasts on dimensions that are present in both analogs…
4. re-representation – altering one or both representations so as to improve the match…
5. incremental analogizing…, and last, the rarest of these,
6. re-structuring – altering the domain structure of one domain in terms of the other…

Gentner then discusses how Kepler used analogy in these ways to effect knowledge change. However, at the end of the article she notes: "I have focused here on the use of analogies in online thought – that is, the processes of analogical reasoning once one has both analogs in mind. But it is obviously crucial to ask how potential analogs come to mind." As noted in chapter 5, and echoed by the findings above by Otis, I argue that the analog (that is, the base of the analogy) is *not* what is primary: the analogy does not first spring to mind and *then* induce a "schema abstraction" (Gentner, 2002). Rather the story (or schema, p-prim, or idealized cognitive model) is primary and this story is what is first accessed. Once accessed or identified, the analog is constructed or identified as a "prototypical" member of the category that this model defines – concretizing or unitizing these schemas entailed in the cognitive model. For clarification and further explanation, consider the following visual "toy" (Fig. 7.1).

Recognizing the irony in making an analogy about analogies to clarify my points, I would like to argue two points: first, that it is having a schema for rabbits that allows you to re-represent this drawing and second, that the schema, and not any particular representation of rabbits, is primary.

3. Joseph Jastrow, "The Duck-Rabbit," from *Fact and Fable in Psychology* (New York: Houghton Mifflin, 1900).



Do you see a duck or a rabbit, or either? (From ***Harper's Weekly***, originally in ***Fliegende Blätter***.)

Fig. 7.1

When you shift the representation of this drawing from, say, the duck to the rabbit you can *only* do so because you know what rabbits look like. You have a "schema" in mind that allows for long ears and tiny nose, and though the rabbit pictured above may not look exactly like any rabbit you have ever seen, you can quickly recognize elements of the "rabbit story" that apply here. For Kepler, if the sun did not seem to give off any kind of energy, or if the intensity of light did not decrease with distance, I would like to suggest that not only would there have been no analog for Kepler to draw but that even identifying this "story" in the case of planetary motion would have been exceedingly improbable: we only see the rabbit because we have seen other rabbits – because our mind knows what rabbit ears look like. Kepler's mind knew properties of light – and so was attuned to recognizing when things decay with distance, that travel through space without being seen and have an effect on objects. This echoes the answer Otis gives to her question, "what was it, I wondered, that drove Ramón y Cajal to keep looking, determined to resolve boundaries between cells when there appeared to be no boundaries at all?" That is, the culture had created a story of boundaries and membranes, so that this story could be identified in other places.

This idea – that our abstract ideas stem from our experiences in the world, has also been argued by Lakoff and Nunez (2001) in *Where Mathematics Comes From*, in which they argue that math is not the abstract ideal that we imagine it to be, but arises from metaphors to physical experience.

> When you think about it, it seems obvious: The only mathematical ideas that human beings can have are ideas that the human brain allows. We know a lot about what human ideas are like from research in Cognitive Science. Most ideas are unconscious, and that is no less true of mathematical ideas. Abstract ideas, for the most part, arise via conceptual metaphor-a mechanism for projecting embodied (that is, sensory-motor) reasoning to abstract reasoning. (Lakoff and Nunez, 2001 p xxi)

Mathematics, as with science, does not simply evolve from the data or from the numbers, but from the "ideas that the human brain allows." And these ideas that the human brain allows are the ideas that it has acquired from the surrounding culture and from sensory-motor experience – they provide us with schemas that we may then project onto new experiences.

Structure-mapping suggests that, to re-represent the drawing as a rabbit, one must first imagine *a* rabbit and then align the features of that rabbit with the features in this drawing. The single representation of a rabbit is primary and is used, together with the rabbit in the picture, to access the more abstract schema. It suggests that we might have to consider a limitless possibility of things – rabbits, cats, dogs, tables – and one by one consider the ways in which the structures of these various potential analogs align with the target. Instead, I find far more plausible that the rabbit "schema," rather than a particular representation of a rabbit, is primary. We access the analog via the schema, rather than the other way around. (Another point to note is that you are *not* drawing an analogy between the rabbit and the duck but rather *re*-representing the drawing, understanding this "stick-out piece" as ears instead of bill.)

Conclusion

The impetus for my thesis and the bulk of my support comes from analysis of student-generated analogies in science. However, studies in the history and philosophy of science, comparative literature and cognitive science have developed stories of theory development that are consistent with my claims that derive from student reasoning. These claims, consistent with student-generated analogies, are also consistent with analogies from philosophy and biology. In particular, the ways in which

- analogies are derivative of the schemas provided by the surrounding culture,
- these schemas are primary and are used to access or construct analogs
- the likeness expressed by analogy is a class-inclusion statement,
- concepts are defined as constraints for class-inclusion, and

- the specific is used to represent the general

are all consistent with generated analogies as assertions of categorization.

In the appendix, I turn from expert scientists' analogies to young students' analogies and find patterns that are reminiscent of the findings reported here. I will return to the ideas from this chapter in the following chapter in which I consider the implications for instruction: if this is what science looks like, and if this is how scientists construct theory, there are profound implications on how students should be taught.

Chapter 7: Implications for Instruction

> How we understand the mind *matters*… it matters for what we value in ourselves and others – for education, for research, for the way we set up human institutions, and most important for what counts as a humane way to live and act… Our ideas about what people can learn and should be learning, as well as what they should be doing with what they learn, depend on our concept of learning itself. It is important that we have discovered that learning for the most part is neither rote learning nor the learning of mechanical procedures. It is important that we have discovered that rational thought goes well beyond the literal and the mechanical.
>
> -Lakoff, 1987 (Preface)

Introduction

The above quote is from a 1987 publication by George Lakoff on categorization. He claims: "it is important that we have discovered that learning for the most part is neither rote learning nor the learning of mechanical procedures… that rational thought goes well beyond the literal and the mechanical." My claims with respect to analogies echo the findings that Lakoff hails in the preface above. In the 17 years since this publication, how has instruction responded to these important discoveries? What would a response to such findings look like in practice? How should they be incorporated in the classroom? In this chapter, I begin with a critique of a relatively standard approach to analogy-use in the classroom. I then highlight three important implications that this thesis, with its focus on student-generated analogies and the categorization interpretation of these analogies, has for instruction. The first is that student-generated analogies ought to be a goal of science education. The second relates to an appreciation and understanding of the manifold nature of students' minds. And finally, when conceiving of analogies as a form of categorization, questions and goals regarding transfer change. I then present examples from analogies in this dissertation, from the literature and from my own teaching that illustrate these implications in practice. The relationship of these implications to the National Science Education Standards and to calls for a greater diversity in science will be explored.

A critique of standard analogy use in classrooms

Lulis, Evens and Michael (2004) report on "How Human Tutors Employ Analogy to Facilitate Understanding" in the context of medical school students receiving tutoring on the heart and its baroreceptor reflex. The tutors in this study are referred to as "expert tutors" and their practices are being studied for the creation of an electronic tutoring system based on the computational model provided by the Structure Mapping Engine (Falkenhainer, Forbus, and Gentner, 1986). I present this here as an example of what is considered (by some) to be best practices for analogies in education and offer a critique of these practices. All transcript quotes provided below are from Lulis, Evens and Michael (2004). Figure 7.1 (from Scott and Schactman, 2004) below provides a schematic of the heart to help the reader understand the conversation:

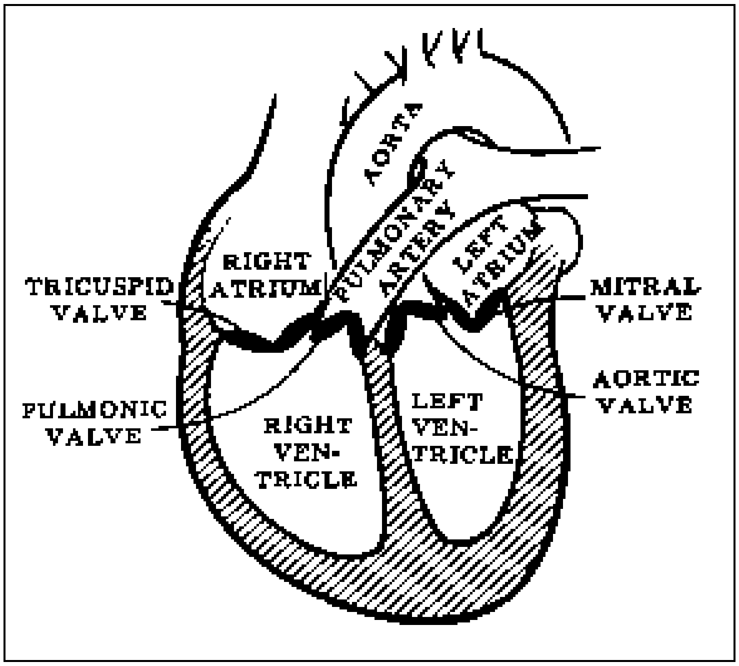


Fig. 7.1

Student:	If I make an analogy of you try to fill a sink with water and you –
Tutor:	Try to fill a balloon with water, since that's what we're dealing with, a distensible object.
Student:	Okay.

Following this, Lulis et al write:

> The following structures underlie what the tutor does (as discussed in Lulis & Evens, 2003; Lulis, Evens and Michael, 2003):
>
> Structure for the balloon:
> - fill a balloon with water
> - it will be distend
> - the pressure in the balloon increases as it distends
>
> Structure for the heart
> - fill the right atrium
> - the right atrium will distend
> - the pressure will increase as it distends
>
> The above example demonstrated the effectiveness of the accepted structure mapping approach of connecting new knowledge to knowledge already understood by the student. As a result, the student develops a better understanding of the new concept (Gentner, 1983, 1988; Goldblum, 2001; Holyoak and Thagard, 1995).

This is the first analogy mentioned in the article and it is applauded by the authors as effective because of its ability to connect knowledge about the heart to "knowledge already understood by the student." The veracity of this claim is dubious – the student has not demonstrated any knowledge of pressure in balloons – but the greater point I would like to argue against is the idea of what learning *is* that is presented in this brief transcript. The tutoring offered in this transcript values content knowledge over the ability to think scientifically: the role of the teacher is to "correct misconceptions" (Lulis, Evens and Michael, 2004). The primary goal of instruction was to "develop a better understanding of the new concept" and not to increase the student's ability to create his own models, evaluate them on his own for their goodness of fit and recommend new models if the fit is poor. The student has constructed a model of the heart as a sink and is immediately cut-off and told, instead, to model the heart as a balloon. This is deemed effective because of the balloon's structural map to the heart. I argue that this may be counter productive instruction because the student is actively discouraged from pursuing his own analogy. In fact, depending on how his analogy played out, it could be seen as more deeply structural than the tutor's as it did not rely on superficial similarities, such as distending. The pressure at the tub's outlet will increase with increasing volume of fluid. This relation between volume and pressure, in fact, is not altered by the tutor's prompting. That the student has not changed his "misconceptions" and is still not creating the analogy that the tutor wills is evident in the following transcript from a later session with the tutor as he states that size will:

Tutor:	We can look at the central blood chamber that means the big veins and the atria together as though they were an elastic chamber. Is that not correct?

Student: Yeah, and the heart is the pump.
Tutor: Well, let's stick to this elastic chamber and look at it first more or less in isolation. If you have an elastic chamber what are the things that determine the pressure inside that chamber?
Student: Size.
Tutor: No.
Student: I mean if you – . I mean – . Area is one but I gather for the heart –
Tutor: Area of what?
Student: Area that – I mean if you want to know what the pressure is of a gas or well liquids aren't that – . We're not talking about gas, we're talking about liquids. And liquids aren't affected by size much because you can't compress the molecules that much.
Tutor: Oh, you mean the volume occupied by the liquid, expansion and condensation of the liquid. No. That's not an issue.
Student: No, because we're talking about liquids and liquids aren't affected. Like with gas, besides the container matters a lot –
Tutor: Let's throw away this atria central venous system and take instead something inanimate elastic stretcher, say like a balloon. Right? What determines the pressure inside the balloon?

In this transcript the student again asserts an analogy the heart is like a pump, and is cut-off from continuing with this analogy. Instead, the tutor wants to focus on the "elastic chamber"-like properties of the veins and atria and why it is best to consider the atria as elastic chambers and *not* a pump are never made clear. The tutor is not taking advantage of the student's analogy to try to understand the student's thinking. Even to the objective of content understanding, the student's analogy can give the tutor information to help with diagnosis of student difficulties

When the student is asked what affects the pressure in the atria (the upper chambers of the heart), he offers size – which is reasonable and predictable from a sink analogy of the heart. However the tutor clearly has other factors in mind, and flatly responds "No" to the student's ideas. But the student, having never understood the failure of his heart-as-sink model or heart-as-pump model, is then clueless as to the "correct" answer that the tutor desires and seems baffled. Similarly, the tutor misunderstands the student's reasoning, perhaps interpreting "size" as being not the volume of blood in the vein, but, perhaps, the volume occupied by a fixed amount of blood. The tutor cuts off the student and provides an analogy to balloons – which are, of course, filled with the very thing the student just determined as an important factor: gas instead of liquid.

And finally, there is a student-generated analogy in which the student proposes that the heart is like a traffic cop. The following session was an online tutoring session and the transcript is a written transcript between the two:

Student:	Would it be a reasonable analogy to look at the heart like a traffic cop? If it slows down the rate of blood flow (lets fewer cars through) then there will be a backup behind it (a backflow of blood prior to the heart, and therefore an increase in CVP [central venous pressure]) and fewer cars coming through (less blood coming out of the heart and therefore a decrease in MAP [mean arterial pressure])
Tutor:	The analogy is OK. But just as traffic jam does not occur because cars back up, the increase in CVP caused by a fall in CO [cardiac output] is not the result of blood BACKING UP. Everything goes in one direction.
Student:	Well, slowing down would be a better way to put it, then.
Tutor:	Yes. A traffic jam caused by everybody piling into the same area at once.

The authors (Lulis, et al) describe the passage above as follows:

> "… an analogy proposed by the student between the heart and a traffic cop. The mapping between these analogs is not correct; the tutor proposes a more suitable analogy between the heart and a traffic jam."

But in what way was the analog "not correct?" Clearly the tutor found something wrong. The tutor mistook a "back up" for "backing up" – but slowing down for the traffic cop and creating a "back up" never necessitate a physical reverse of direction. To "correct" the student's misunderstood idea, the tutor recommends thinking of the heart as a traffic jam.

In summary, the tutor has a concept that he/she would like expressed by the student, and this tutor has a particular analogy in mind for conveying this concept. When the student proposes alternative analogies (which may not even be incorrect), the tutor, concerned with establishing the correct scientific answer in the student and not concerned with fostering the scientific reasoning abilities of the student, cuts off analogy generation. While clearly this is not effective in fostering scientific creativity, it also is not clear that it dislodges any supposed misconception that the student has.

Furthermore, the interpretation of the authors, who apply a rigorous structure-mapping technique to analyzing these analogies, suggests that the heart cannot be conceived simultaneously and fruitfully as both a pump, elastic chamber, sink, traffic jam and traffic cop. By their interpretations, the structure implicit in these models is either right or wrong, a misconception or a correct idea. The task of the instructor is to give the student the correct analogy for the purpose of correct conceptual understanding.

I would like to note that the instruction described above for implementation in an electronic tutoring system is described not by the creators and proponents of structure-mapping, but is instead one interpretation of how structure-mapping may be employed in the classroom. A more fruitful manner in which to employ the concepts behind structure-mapping is case-based reasoning, and the merits of this approach are detailed by Gentner, Loewenstein and Thompson (2003). The approach described in that article focuses on ways in which one may foster analogical retrieval and transfer in the students, as opposed to content knowledge. Yet one message is still the same: the students must be told the analogical cases in the first place before abstracting from these cases on their own.

As an alternative to instruction *by* analogy, with the focus on misconceptions and correct ideas, I argue instead for instruction that fosters analogy and encourages the students to create their own analogies and determine the merits of them. With an appreciation for the role of chains of analogies (analogy "hopping"), the initial analogy's merits are not in the conceptual correctness in a structure-mapping sense, but instead the analogy is meaningful for the activation of resources: schemas and cognitive models that may help them negotiate a more meaningful analogy and understand the ways in which various analogies are applicable, so that the heart can be conceived of as a pump, chamber, sink, traffic jam and traffic cop.

Implications for instruction

<u>*Students ought to generate their own analogies*</u>

Studies on creativity – creativity in general and creativity in science – have shown

that

> the essence of creativity is to be able to view a situation or an object from two different frames of reference, or two 'unrelated matrices of thought' (Koestler, 1964). This is sometimes referred to as *restructuring*. Restructuring, thus, is often viewed as being able to see a problem in a 'new way' that is fundamentally different. However, defining creativity in this way merely begs the question of what constitutes a 'new way,' a 'different frame of reference,' or 'an unrelated matrix of thought?'… A new perspective is defined here as re-representing an entity or a situation from one 'ontological' tree of concepts and categories to another ontological tree of concepts and categories…
>
> -Chi (1997)

In this thesis, I have argued that analogies are assertions of categorization that violate expected categorization. In short, analogies are powerful precisely because they do this thing that has been identified as the essence of creativity. It is not a leap, then, to suggest that a goal of education should be to encourage and foster creativity by teaching students to generate and elaborate analogies.

Furthermore, using analogies is part of what it means to do science. "In studies of the work in molecular biology laboratories, Kevin Dunbar found that the most creative and productive labs showed a high frequency in the generation of analogies and the sustained collaborative elaboration of analogies" (Kittay, 1997 p. 400). In particular, Dunbar found that when formulating hypotheses scientists rely on "far transfer" analogies: analogies that rely on structural and not superficial similarities. Given that doing science, then, entails generating and elaborating analogies, science classrooms should encourage the generation and elaboration of analogies.

Of course, analogies *are* frequently used in the classroom. In a recent article by Richland, Holyoak and Stigler (2004), they report on an in-vivo study of analogies in eighth grade mathematics classrooms. As with Dunbar's finding, Richland et al found that analogical reasoning is quite prevalent and even far transfer analogies are not uncommon. However, it was not the students but the teachers who generated the vast majority of analogies in their study, and these analogies were aimed at achieving goals relating to conceptual understanding: getting students to solve problems correctly or understand why they are applying a certain method. These analogies, then, are not indicative of *students'* use of analogies in the classroom. Even more troublesome is that the concerns raised in Richland, Holyoak and Stigler's (2004) article were not regarding this fact. Instead, the concerns questioned whether or not students were able to interpret the teachers' far-transfer analogies. Teacher-generated analogies are important and can play a role in encouraging student-generated analogies; but they should be responsive to the students' ideas and not solely for the purpose of imparting knowledge.

These findings and the concerns are representative of the pervasive focus on the *facts* of science as opposed to the creative inquiry that is involved in *doing* science, a focus reiterated in classrooms by a reliance on textbooks and testing. The question that tests and textbooks answer is: how can I get my students to know *x*, and how can I determine whether or not they have learned *x*? Similarly, cognitive science literature on analogies (such as Gentner & Gentner, 1983; Clement, 1983; Glucksberg and Keysar, 1990; Gibbs, 1992) consistently focuses on participants' abilities and processes regarding the *interpretation* of analogies and only very rarely (Hofstadter, et al, 1995) the *generation* of these analogies. The question that is unanswered by these textbooks, tests and studies is: how can I help my students learn how to learn? How can I evaluate whether or not they will be creative scientists? How can I help them to create their own theories?

Of course, one might expect that presenting students with carefully constructed analogies will aid them in constructing their own analogies, and so the teacher, as presenter of analogy, is modeling a behavior for the students that they may in turn adopt. But such analogies are not responsive to the schemas that the students have and may seem disconnected from their own lives. Furthermore, simply modeling behavior for students without giving them time to practice that skill on their own will not always result in the students adopting that behavior. There must be space for the creation and elaboration of analogies *by* the students. I will detail in a later section what this might look like in practice. First I highlight implications from my research on the interpretation of student-generated analogies.

Expect variability and multiple analogies

To borrow again from Lakoff's quote that introduces this chapter, "It is important that we have discovered that learning for the most part is neither rote learning nor the learning of mechanical procedures. It is important that we have discovered that rational thought goes well beyond the literal and the mechanical." The discoveries that Lakoff refers to are discoveries in linguistics in general, and categorization in particular. To this, I would like to add that it is important that we have discovered that children – even young children – can and do create significant, structural, "far transfer" analogies. It is important to recognize the ability of students to shift representation of the base in analogies. It is important to recognize that analogies often appear in multiples, that they have a strong similarity to categorization, that they can be used to make claims of structure, of epistemology, and of ontology.

In what way are these findings important for education? Primarily it is an implication for education research. First, if we value the generation of analogies it is important to understand the cognitive work that analogies do. Far from what structure-mapping suggests, generated analogies are not simple pairwise projections from a base to a target and learning, as Lakoff identifies, "is not the learning of mechanical procedures." That is to say, applying the algorithm of a structure map is *not* the heart of analogy and while it may promote content knowledge acquisition, it does not necessarily promote creative and insightful reschematization. The structure-mapping application of analogy limits the power of an analogy – it can only hold particular inferences, and those inferences must come from a structure that exists in a stable, fixed representation in the single base. Analogies are powerful not because of a projection from a single known phenomenon (the base) onto an unknown or misunderstood phenomenon (the target), but because of their ability to completely change the categorization of the target. And categories, because of their basis in a particular cognitive model, can make powerful claims on the target. These claims are not limited to what the base alone conveys, but, more abstractly, what the category and its associated cognitive model imply. Furthermore, because of this it is not imperative – or even reasonable to expect – that students reason with conceptually (that is, structurally) isomorphic analogies. Rather the analogies may enable other students to access alternative models and follow chains of analogies to arrive at an appropriate understanding.

A second claim is that, if we value analogy generation, we ought to know where to look for it. Young children have been described as unlikely to create analogies of "far transfer" (for example, Carver, Price and Wilken, 2000). I will take issue with the concept of "far transfer" in a later section, but for now it is important to note that second graders were able to compare magnets to clay and electricity. Fifth graders compared a swimming pool to space, a cup of water to a toy cat swinging in a basket, and running with keys to falling off of your bike.

There is not, then, a particular age in schoolchildren when one should not expect and encourage analogy generation from students. The sophistication and facility with analogy surely increases with age, but analogy – even far transfer analogy – is prevalent among students from at least first grade on.

A third claim that has implication for instruction is the claim that this research makes on the ontology of mind. Not only are the concepts that are being employed in analogy the concretization of a set of activated schemas, but the concepts themselves are variable. A concept can be employed in an analogy for its epistemology, its physical behavior, or its general ontology. A concept can shift representation, as with money being used to represent the "hard" ontology of currency or the "fluid" ontology of net wealth. For this reason, science education researchers should recognize the variability of student reasoning: the base of an analogy is not a single, unitary concept that is fixed in the student's mind, but highly variable. Teachers need to allow students to express their senses of a concept, to identify the cognitive models they are employing in defining this concept and allow for a shift in this representation. (Clarifications of these ideas are provided in the section below on these implications in practice. Significant to this claim is that the initial analogy does not need to be conceptually correct to be generative of meaningful science – conceptually and epistemologically.)

A reconsideration of the idea of transfer

Finally I would like to call into question the ideas behind "transfer" – a holy grail of education. Transfer is described as "the ability to extend what has been learned in one context to new contexts" (Bransford, Brown, & Cocking, 1999). Laboratory-based studies that address whether or not students transfer a particular technique or theory from one domain onto another have demonstrated that far transfer – transfer in which there are few superficial similarities – is difficult and rare. "Near" transfer, in which there are more feature similarities between the base and the target, are more common but not consistently achieved either (Holyoak and Thagard, 1989). In the study reported above by Richland, Holyoak and Stigler (2004), it was found that, unlike in the cognitive science laboratory settings, analogies teachers present in classrooms are often far transfer analogies. Dunbar's research in science research groups found this as well – though the majority of analogies were within-domain, far-transfer analogies played a significant role. Similarly, my findings in science classrooms and discussions show that instances of transfer, as measured by analogy use, are not difficult to find, with far transfer demonstrated across many different ages of students. But I would like to call into question the very *idea* of far transfer as a meaningful distinction. In a category framework of analogy, one would not expect far transfer to be as difficult *if* the base of the analogy is a category prototype. Furthermore, near transfer, because it does not require a re-categorization of the target, is not an analogy in the sense that it does not shift ontology – it is routine categorization. Again, this is a choice of definition but one that can provide a more formal model for what is meant by transfer. Perhaps the idea behind transfer that we should be focusing on as educators and researchers is the ability for students to draw analogies that re-categorize the target from an expected or automatic categorization to a novel one, the ability to make inferences with this new categorization, and the ability of students to identify meaningful and prototypical choices for the bases of their analogies. Focusing on whether or not the base of the analogy shares superficial features with the target misses the point of analogy: the selection of a prototypical member of a category to serve as a base in expressing a reclassification of the target. When a student is asked what will happen to keys if you drop them while running, is the analogy of dropping a rock from a bus "near" or "far" transfer? How would that compare to, say, a student drawing an analogy to walking and dropping coins? The features of the second analogy are certainly "nearer" to the base, and dropping coins while walking surely happens far more frequently than rocks are dropped from buses. But in discussions with students the first analogy (or similar analogies) is *far* more frequent than the second (which I have never heard). How, then, can we claim that far transfer is hard and near transfer easy? Instead, I argue that transfer is better understood in terms of a change in cognitive model, with prototypical instances as more accessible instances of a particular cognitive model.

Implications for instruction in practice

Examples from transcripts

If these implications are taken into account in a classroom, what will that look like? The transcripts peppered throughout this dissertation prior to this chapter give an idea. Throughout this dissertation are analogies in classrooms that are constructed by students and by teachers who are responsive to those students. To detail analogy generation by an instructor that is done in a responsive manner, consider the transcript presented in Chapter 1 and contrast the use of analogy here with that by the tutor at the introduction of this chapter (transcript 1, lines 53 – 71):

> Lea: … the pan is more dense so they're able to slide across it like they can ice skate across the [inaudible] here. So that's why they move around more 'cause it's more dense so they can slide across it more and the Styrofoam is less dense and so they get stuck in it. Like so they can't move as much.
>
> Instructor: Lea I want to add – I think you're sort of what I when I hear you talk I'm thinking of like, pouring water into a sponge versus pouring water onto a hard surface. [Lea: Yeah.] Like this sponge is actually less dense and there's room for it to absorb the water and the you know if you pour it onto something hard there's no room for it to absorb. But Christie – I mean this is an interesting thing you guys are both thinking that density is important but one of you is thinking that more density means one thing and one of

you is thinking more density means the other thing. Is that is that – am I right? [Christie: Yeah.]

And in lines 113 – 121:

Lydia:	I was going to say I think the pie plate is more dense but I do think that it's inside not outside because if there's more space to travel then the molecules can't get from one space to another easily but it's all [inaudible].
Instructor:	Oh so it's like stepping stones [Lydia: Kind of.] like in the Styrofoam it's really far to the next stepping stone so it's like can't get there I'm stuck here. [Lydia: Right] but in the metal the stones are really close together so I can kind of walk across. [Lydia: Yeah.]

In addition to creating a classroom in which students are encouraged to construct their own models and explain these with analogy, the instructor constructs analogies as well. However, rather than constructing analogies for the motion of charged particles and presenting them to the class, the instructor constructs analogies that are responsive to the ideas from the students – elaborations on their ideas ("oh, so it's like stepping stones") as opposed to contradictions to their ideas or even unrelated to their ideas (as was the case in the tutor's analogies presented above in the previous section).

Examples from the literature

Another example of responsive use of analogy in the classroom has been detailed in May, Hammer and Roy (2004). The class is considering how earthquakes happen and one student constructs a lava/pressure model of earthquake:

Skander:	That's what I mean. A rock could – like, the volcano is this big [motions with hands] and you're on this side of the ground, a rock could go in, and pretend like, pretend the lava is water and the giant rock is a cube [Teacher: okay] it goes up and since it's blocked the ground has to shake which causes it to crack open so it it'll actually like go up farther.
Teacher:	Okay, so you're –
Skander:	So it's like you're actually flooding the cup of the water.

Teacher: And so the rock acting as the ice cube is flooding the lava so it has to come up and go out?

Skander: It doesn't have to, it just makes the ground come, it just needs space to go up. It's just causing it to shake and crack open.

Although this analogy is suggesting a mechanism that is incorrect for understanding earthquakes, the teacher does not contradict Skander (as the tutor does at the beginning of this chapter) or call on a different student, but allows the student to continue with the generation of analogy. In the following section I follow an example from my own teaching, in which I detail how incorrect analogies can play out in the classroom.

An example from my own teaching

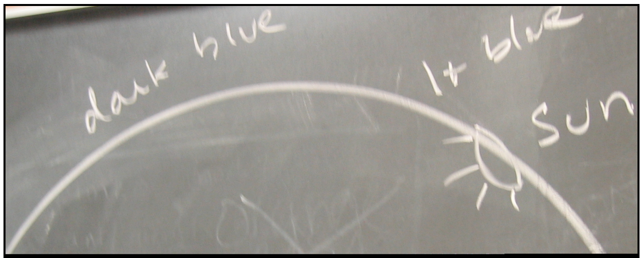
Here I present an overview of a week-long conversation in a high school science class regarding why the sky is blue. This conversation was not recorded; data comes from notes and photographs of the blackboard, where ideas were collected. I was a co-instructor of this course and I did not refrain from interjecting my own analogies for the students. The class is at a state funded summer program for "academically and intellectually gifted" high school seniors. There are 27 students in this class. Most of these students are from public schools in small towns and rural areas. At the time of this conversation, the students had been in school for four weeks. A typical day began with either a "Fermi Question" (a question requiring students to answer a question numerically for which there was not enough information to determine the exact answer) or a "Science Talk" question (a more conceptual type question, generally about a physics concept). By the end of the summer students pose and answer their own questions as a class. In the beginning of the fifth week, the question was raised, "Why is the sky blue, and why does it get darker the further up you go (like in an airplane)?" In groups of 4 they addressed this question, and, as the teacher, I instructed them: “Don’t just say ‘because of the atmosphere.’ Be sure you say how you think the atmosphere creates blue.” (Not a direct quote.) As they worked in groups, my co-teacher and I circulated around, talking with each table and having them sketch their ideas on dry-erase boards to share with the class. After about 20 minutes, I addressed the class as a whole. I had noticed that some tables were thinking of the atmosphere as a filter, and others as a prism. I asked if all of the groups had one of these ideas, or were there more? Between the six tables, there were the following ideas:

- The atmosphere is undergoing atomic emission.
- The atmosphere is like a prism: different angles to that prism see different colors.
- The thickness of the atmosphere somehow matters.
- Energy loss in the atmosphere creates a reddening of the light.

(The “filter” theory was discarded early on by a table that recognized that this would block out every color except blue.) In addition to these initial, whole-group theories, other theories were proposed by individuals:

- Thin film interference in the layers of atmosphere preferentially select blue light.
- Distance from the sun matters. (A correlation between planet colors and the order of colors in the rainbow, the class never seriously entertained this theory.)
- Reflection from the blue ocean creates a predominantly blue sky. (Quickly discarded this theory.)

Perhaps because of the charisma of the proponent of the theory, the “atomic emission theory” was adopted early on as a theory to consider in depth. The students recognized that this theory had to account for red sunsets and red pollution, green flashes and green tornado skies. It had to account for the colors of skies on other planets (both of my classes that addressed this question became very focused on the color of other atmospheres) and for the sailors' aphorism: "Red skies at morning, sailors take warning; red skies at night, sailors delight." One student noted that skies seem a more deep or crisp blue in the winter, another that dawn was not as red as dusk. After lunch one day, students came in to tell me that the sky is light blue – almost white – close to the sun and a darker blue away from the sun (as drawn below).



[redacted]

Fig. 7.2: Description of shades of blue in the sky

In negotiating these constraints, the students could incorporate some ideas from atomic emission, but not all. The theory grew to be an atomic emission theory combined with a weather component to explain other colors and a filter component to block ultraviolet light. A question that was could not be addressed by this theory concerned why white paper does not look blue. After too many ad hoc components were added on to the theory, the students as a class decided it could not be correct. (Questions and comments addressing the "atomic emission theory" are in the figure below, a snapshot of one blackboard. All student comments and questions were noted for the whole class on the blackboard, in addition, many students took notes and represented their ideas for the class on their group's dry-erase boards.)

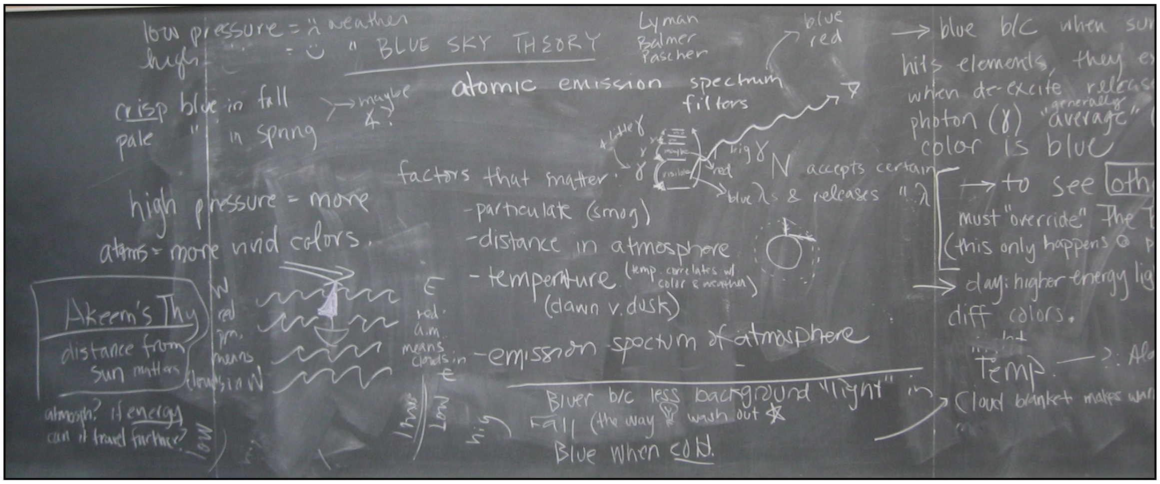


Fig. 7.3: Blackboard notes of class discussion

We then revisited theories they had mentioned on the first day of discussion. In writing them on the board, I asked one student about his thin-film theory. He commented that it was "stupid" and we shouldn't consider it. Knowing that this student had been questioning in the past how bubbles get their oil-slick-like colors, I pressed him for his rationale in creating the theory. The bubbles were mentioned and I pointed out, using his experience with bubbles, that really what all of these theories have in common is that they are a way of using white light to get colored light. Bubble "juice" itself is clear and has no color, nor does a prism or neon gas (a model for atomic emission) or "red shifted" white light, and white light bouncing off of a blue surface will then appear blue, even on "colorless" white. All of these systems have no apparent inherent color and yet they all have a mechanism by which they attain color. More importantly, the students recognized that these mechanisms were inherently different, so that a prism model was not the same as an interference model or an emission model or a red shift model.

At this point I note several ways in which I, as a teacher, was incorporating the implications for instruction mentioned above: my rationale in structuring the course in this way and my interpretation of the students' comments.

First, I know why the sky is blue and could easily have delivered a 10-minute lecture on the topic, expeditiously explaining why the sky is blue – incorporating analogies if helpful. (Although some questions they brought up are ones I had never considered and would have been hard pressed to answer!) Moreover, I know that the students do not know enough physics to correctly answer the question of why the sky is blue. The pattern of dipole radiation that is responsible for our blue sky is beyond the scope of a high school physics class, although the basic story of scattering is one that they could reason about and understand. My reason for asking the students to develop their own models reflects my contention that education should encourage students to learn how to create their own models and draw their own analogies. I also believe that it is possible to address this question scientifically even if one does not know enough science to arrive at the "correct" answer – for though Newton did not know enough about light to understand reflection he addressed these questions in a scientific manner and arrived at questions that proved important to later research. At any point, I could have posed questions to them that would have poked holes in particular theories, but I chose to allow the students to find these themselves, as part of what it means to do science.

Second, I did not assume that the analogies arose from a pairwise analysis of target and base: initial analogies were identifying ways in which one can get color from colorless things; the analogy springs to mind before the structures (in a "structure mapping" sense) can be evaluated and checked; this evaluation was done in large part as an entire class and was not part of the analogy process for any single individual. These analogies, the initial models proposed by the students, echo the analogy process that Miranda used (in Chapter 4). In the same way that the overturned cup of water is not always like an overturned cup of water – at times it is much more like a toy cat swinging in a basket, so too is air not always like air: at times it is more like a prism, a neon sign, or a hologram. An understanding of the analogical base as a fixed structure cannot expect and understand the generativity of other analogies. Expecting the student might draw a series of analogies, finding her way from that first idea to another and to another, a teacher would not be so concerned that the first analogy be *correct*. If we think of analogies in target-base pairs, that first mapping would be critical. But if we think of analogies as activation of different sets of resources, that first analogy could lead to a second. In fact, few students knew how a prism worked – the deep structure of the analogy they were proposing, or details about atomic emission. Discussions of how these things worked were figured out as a class at times, with a few brief (five minute) lectures from me. These explanations and discussions evolved into new models based on new analogies: an ant/giraffe model of light moving through media that explained why red is less impeded than blue, a "marching band" model of refraction to explain why light bends, and a trombone/piano model to explain the difference between a "chord" of colors and a pure color. From this arose new questions: is our blue sky an "average" color or a pure color? Shouldn't we see a green sky at times if our atmosphere is a prism? If blue is "impeded" in the atmosphere and so gets to us later, how does that affect the colors that we see? Representations of air, prisms and bubbles are all variable, so that they may belong to similar categories (things that are colorless and yet have color) and distinct categories.

Following negotiations of several candidate theories over a five-day period, the class settled on a "prism" model for creating blue skies. They still had a two questions: why we don't see a green sky between the blue day and the red night, and by what mechanism do long wavelengths bend less than short ones (we had an "ant/giraffe" analogy, but it seemed more mnemonic than a model). But these questions aside, the class was relatively confident in their model and asked for the "right answer." I then read them a passage from the New York Times' Science Tuesday section. (Coincidentally, this article on colors in nature was published the day before I had promised to tell them "the answer.") The passage reads as follows (Angier, 2004):

> Another type of structural color results from the incoherent scattering of light, also known as Tyndall or Rayleigh scattering. The sky is the most renowned example of such scattering at work. Sunlight and its complete spectrum of radiation falls on the atmosphere, a diffuse wilderness of particles. Most of the light rays are too wide of wale to be impeded on their journey earthward, but blue light is so short-waved that it invariably meets a molecule it cannot ignore and is scattered across the sky.

Following our five-day discussion on why the sky is blue, this passage ("the answer") was met with puzzlement. The students were upset that it said nothing about green, or why sunsets are red. The phrase "too wide of wale to be impeded" was written off as utterly incomprehensible – how can something be too *wide* to be impeded? Length, not width, was the determining factor in our discussions of blue skies. In our discussion following the reading, the students determined that the passage was vacuous. In particular, there was no reason for them to believe this model over any other model; the explanation did not address any of the questions that they still had; the explanation did not express why other models fail; and it never explained that the scattered light had to eventually reach your eye to be seen – a hang-up that had troubled many students in our discussions. Rather, it seemed to suggest that if there is blue light scattered among the atmosphere we will necessarily see that atmosphere as blue.

The blue-sky explanation from the New York Times still uses analogy, albeit quite loosely, as a tool for conceptual understanding. Describing a photon as "wide" is a metaphor: photons do not have much physical extent in the direction perpendicular to their propagation. But I am not primarily arguing against teaching via analogy because the analogy that was provided by the article was provided was not one that the students could make sense of; rather, by having the students build their own models by drawing from analogies to systems with which they were familiar, and then exploring why they hit on these models and negotiating the implications of these models, created a far richer understanding of the material, developed in them a sense of what it is like to "do" science, and allowed the students to quite realistically model the interactions and discussions one would find in a research group.[1]

Finding analogies in the classroom

What kinds of discussion topics foster analogy generation? As noted earlier in the thesis, they are negative assertions – such as a cup of water that doesn't spill, colorless air that looks a particular color, or physics problems that cannot be solved from first principles.

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[1] There is not an explanation that is detailed and coherent enough about why the sky *is* blue that will enable students to understand why other models fail. Nor can a detailed explanation help students learn how to create theories and models on their own.

Lakoff (1987) notes that "but" can often be used to identify cognitive models. For example, in the phrase "She's a mother, but she works," the "but" acknowledges that there is something about "motherhood" that is (culturally, at least) at odds with having a paying job. Similarly, all of the topics above have that "but" quality to them (I wrote them in a way to highlight this aspect, of course). In some way these scenarios do not have the expected outcome, meaning that the topic is in some way at odds with an idealized cognitive model. And so, in order to make sense of the scenario in a scientific way (meaning coherent with known phenomena and experience), the topic must be situated in a different cognitive model. And, since cognitive models give rise to categories, to situate the topic in a new and appropriate cognitive model this topic must be granted membership into a new category. The category has a prototype and this prototype is selected via an analogy to demonstrate the new category and its associated cognitive model.

Many, but not all, of the topics above were chosen for their ability to be reasoned about in terms of "tangible" ideas, which is a part of analogy[2]. Another element of analogy is the change of categorization. Science, and physics in particular, is rife with paradoxes[3], and these paradoxes can be resolved within science. One tactic I have in teaching is what I refer to as the "what's weird." When a student performs an experiment or makes an observation and thinks, "that's weird," I tell them to stop right there and ask:

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[2] In my class, we were having a discussion of Kuhn's *Structure of Scientific Revolutions* and by modeling theory building we modeled paradigm shifts. The focus was not on analogies (though doubtless my interest in them fostered their construction).

[3] My graduate quantum mechanics professor, Dr. David Boulware, lectured one day on the redundancy of the phrase "apparent paradox." In physics, he claimed, all paradoxes are only apparent and can be resolved.

why is this at odds with what you would expect? Identifying the story that you expected to take place and recognizing the rationale for that story allows you to understand the schema that you were applying and other examples of that schema. Then the students are asked to "make sense of it." How can you tell this story in a way that the initially unexpected outcome makes sense? In doing this, analogies are frequently generated.

The National Science Education Standards

Another question I would like to raise and answer in this chapter is whether these implications for instruction are consistent with the National Science Education Standards (NRC, 1998). In fact, the Standards make no explicit reference to encouraging students to generate and critique their own analogies. However, analogy generation and use is a powerful tool for addressing many of the goals set forward in the National Science Education Standards, in particular those involving the "abilities necessary to do scientific inquiry." These are:

- Identify questions and concepts that guide scientific investigations
- Design and conduct scientific investigations
- Use technology and mathematics to improve investigations and communications
- Formulate and revise scientific explanations and models using logic and evidence
- Recognize and analyze alternative explanations and models
- Communicate and defend a scientific argument

As I have argued, student-generated analogies address these goals: they are a key part of how science happens; they often arise when experimental results clash with expectations – a fruitful place to identify questions and guide investigation; they can be the basis for conducting an investigation and constructing a model; the evaluation of analogy is deeply tied to logic and evidence; and analogies are routinely used by scientists in communicating and defending their scientific arguments.

The case for diversity in science

A final claim that I would like to make is more an implication for science – the enterprise and industry – than science education, though the two are, of course, related and to change the enterprise and industry of science one must have educated scientists to effect that change. But I hasten to add that the causes for such a lack of diversity among scientists are perhaps only related to education insofar as education is influenced by the culture of science and the culture at large. Therefore these implications should be not only for instruction but an argument to the culture of science, as any lasting change must come from the source.

As noted in the chapter addressing the history of science, our discoveries – the things we pay attention to, notice, expect and explain – are not recognized objectively. Rather, the theories we create with our science are analogies to the stories we tell with our lives. Though the technology and techniques necessary to identify cellular structure – membranes – in the nervous system had existed for years, they were not discovered until the surrounding culture developed a story of membrane-like countries – dividing up the landscape into distinct separate self-contained units. Though electrical phenomena had been studied for years, the nervous system itself could not be understood until the telegraph was invented and gave us the causal story behind impulses in nerves. To follow an analogy presented in chapter 6, “rabbit ears” in a drawing of a duck are recognized only by people who have seen rabbits. The conclusion we must reach, then, is that people with different stories will notice different things, make different discoveries and have different theories about these discoveries. Their analogies will be different because their stories are different. And surely a diversity of discoveries and theories are a benefit to the enterprise of science. The more that the culture of science, and the culture at large, allow for a diversity of scientists, engage with and allow a diversity of interpretations and theories, the far richer our science will become.

Conclusion

"The essence of creativity the essence of creativity is to be able to view a situation or an object from two different frames of reference, or two 'unrelated matrices of thought' (Koestler, 1964)." And analogy, as this thesis has argued, is an assertion of categorization that places the target in a new or unexpected category. Instruction that fosters analogy generation, then, is instruction that fosters creativity. Furthermore, analogy generation is a crucial part of what it means to do science. This cannot be taught by the careful selection and presentation of well-vetted analogies, but instead by encouraging students to generate and negotiate their own. Classrooms that focus on student reasoning and incorporate the creation of analogy rather than teaching *by* analogy encourage students to be creative and scientific. In doing so, many of the benchmarks in the National Science Education Standards will be addressed. Furthermore, an understanding and appreciation for the role of analogies in science, and the basis of these analogies in the schemas that we bring to our lab benches, can only call for a greater diversity – cultural and gender – in our scientific community.

Chapter 8: Summary & Directions for Future Research

Introduction

> You fight your superficiality, your shallowness, so as to try to come at people without unreal expectations, without an overload of bias or hope or arrogance, as untanklike as you can be, sans cannon and machine guns and steel plating half a foot think; you come at them unmenacingly on your own ten toes instead of tearing up the turf with your caterpillar treads, take them on with an open mind, as equals, man to man as we used to say, and yet you never fail to get them wrong… The fact remains that getting people right is not what living is all about anyway. It's getting them wrong that is living, getting them wrong, and wrong and wrong and then, on careful reconsideration, getting them wrong again. That's how we know we're alive: *we're wrong*.
>
> -Philip Roth, *American Pastoral*

When I began my study on analogies, I was interested in a study on *negative* analogies: that is, the places where our analogies are wrong, when the target and the base of our analogies don't quite match, where these mismatches occur, and what that tells us. I was asking this question having recently sat in on a course in literary theory – a field where scholars have argued that we define our terms and our stories negatively: by what they are *not* instead of by what they *are* – and noticing parallels between this idea, based in literature, and my experience in the lab and as a physics teacher. However, the lack of information on student-generated analogies shifted my focus from negative analogies to analogies in general, establishing what analogies are and what kinds of claims they make. Following a summary below, I begin the consideration of directions for future research with a discussion on the literature of differénce and the relationship between this idea and the idea of a negative analogy. I then present a consistency between these ideas of difference and negative analogy and the framework behind student-generated analogies presented in this dissertation. Finally, I conclude with suggestions of a direction for future research – first with respect to negative analogies and then analogies, categories and science education.

Summary

In this dissertation, I began with the argument that student-generated analogies phenomenologically have the properties that have been recognized in categorization research: multiple members, family resemblance, constructed bases with multiple possible representations, and far transfer analogies. Furthermore, these properties are neither predicted nor explained by models of analogy that focus on recall of a base and then an extrapolation of a structure or schema *from* that base. When considering an ontology of mind that allows for this phenomenology, I have argued that a schema-theoretical model of mind accounts for these properties: it attributes schemas (p-prims, scripts, and cognitive models) as the building blocks of mind that become activated and then select and construct concretizations. It has been argued (i.e., Lakoff 1987) that our categories are defined within and derivative of our schemas, and I argue that the base of an analogy is such a category – a representation, constructed in the moment, of a set of schemas. The assertion of an analogy is an assertion that the target of the analogy belongs to the category represented by the base, as opposed to simply a match between the target and the base. Under this ontology, it becomes possible to sketch a definition of analogy that differs quite fundamentally from similarity – a definition lacking from other models of analogy. Analogy in this definition becomes a deliberate cognitive move that acknowledges the presence and possibility of two distinct cognitive models and privileges one over the other.

In considering the directions for future research, I would like to begin by considering this final point above: analogy as a *negative* assertion and a move *from* something – the cup of water is *not* like other cups of water, a beanbag dropping is *not* like throwing a rock from a bus, motion of electrons in a dense media is *not* difficult like the motion of a person through a dense crowd, and solving angular momentum problems in physics is *not* something to be done from first principles. This idea of defining and understanding concepts by what they are not echoes claims from literary analysis, which in turn raises questions for future research.

Negative analogies

Literary analysis and differénce

At the beginning of the 20th century literary analysts were dedicated to identifying similarities between texts – this script that defined a story. Their work focused on determining the story on which all stories were based – thereby reducing all particular stories to the general. Jung (1969) explored the relationships between all myths and rituals. Psychologists (among them Fromm, 1957) developed a theory of fairytale in which all fairytales are variations on a single fairytale theme. But in the 1950's Roland Barthes began to stress the importance of recognizing how things are different – that the theme is not the meaning, but the variation on that theme. Barthes summarizes the task of analysts of narrative in reducing all stories to one model as a:

> task as exhausting as it is ultimately undesirable, for the text thereby loses its difference. This difference is not, obviously, some complete irreducible quality (according to a mythic view of literary creation), it is not what designates the individuality of each text, what names, signs, finishes off each work with a flourish; on the contrary, it is a difference which does not stop and which is articulated upon the infinity of texts, of languages, of systems: a difference of which each text is the return. A choice must then be made: either to place all texts

> in a demonstrative oscillation, equalizing them under the scrutiny of an in-different science, forcing them to rejoin, inductively, the Copy from which we will then make them derive; or else to restore each text, not to its individuality, but to its function, making it cohere, even before we talk about it, by the infinite paradigm of difference, subjecting it from the outset to a basic typology, to an evaluation…. (Barthes/Miller, 1991)

Barthes theory stems from a tradition in semantic theory developed some 40 years earlier. In the 1910's Ferdinand de Saussure developed a theory of "differénce" whereby words (or rather "signs" – the sum total of information from gesture, word, tone, etc.) get their meaning not from a simple one-to-one relationship with the external world, but "one unit has value within the system because it is *not* some other unit within the system" (Tyson, 1999). Concepts are defined in opposition to other concepts.

Laura Otis, whose work was reviewed when discussing the history of science, comments on noticing the following parallels between Saussure and science, retelling her experience in a lab that studied visual perception:

> I was a biochemist, a mere visitor to the lab, but I learned an important lesson that night. The eye, and the regions of the brain that interpret visual information, respond only to changes, to borders between light and dark. There are cells that fire only when a bar of light moves horizontally, and cells that fire only when it moves vertically… there are no cells that respond to a uniformly illuminated screen, with no movement, no edges, and no borders…
>
> Fresh from the lab, I learned the same lesson in Jonathan Culler's introductory course on literary theory. Explaining Saussure's idea of how words were paired with objects, Culler proposed that we define concepts not based on what they are, but on what they are *not.* When defining something, we typically compare it to something similar and then, like the eye, focus on the way it differs from the concepts most closely related to it. A cow, for instance, has four legs like a horse, but it is fatter. There is no natural match between a word and the thing it represents; no positive assertion of a thing's identity, just as there will be no firing in response to a blank screen, even when it is brightly lit. Like our visual system, we create meaning only through the differences we perceive and the boundaries we believe are present. (Otis, 1999 p. 1–2)

Otis, a professor of comparative literature, presents this story at the beginning of her work on membranes to note two things: one, she is interested in boundaries – this book explores the concept of membranes in political and scientific climates, and, two, that the boundary "between the humanities and the natural sciences as a another boundary arbitrarily drawn." (Otis, p. 3.) I present it here to revisit the idea of the negative assertions that are implicit to analogy.

Negative analogies

I have argued that analogies involve more than just similarity, but also dissimilarity – they dislodge the target from its expected categorization and schema and place it in another one. The claims of Barthes and Saussure, and reiterated by Otis, suggest that perhaps the most significant function of the analogy is the "dislodging," negative part of analogies and the contrast the analogy highlights: what is crucial is not the claim that *a* is like *b* but instead, implicit in this claim, that *a* is not like *c*. However, the idea of differénce also suggests that there is something negative inherent in the "*a* is like *b*" claim – for Barthes claims that "[reducing all stories to one model is a] task as exhausting as it is ultimately undesirable, for the text thereby loses its difference." It is this idea that I suggest as a significant area for future research.

When drawing analogies between two cases, the significance comes not only from the similarities between the two compared cases and the difference between the target case's expected and asserted schemas, but also the differences between the two compared cases. The value assigned by the analogy also comes from the difference between the items that are asserted to be members of the *same* category. It illustrates what is essential to the category as well as identifying what is unique about the phenomena. Furthermore, as Barthes (1991) notes, this difference is

> not what designates the individuality of each text, what names, signs, finishes off each work with a flourish; on the contrary, it is a difference which does not stop and which is articulated upon the infinity of texts, of languages, of systems: a difference of which each text is the return.

By paying attention to how our target differs from the base, and doing so in a dynamic way, we set up a dynamic science – one that evolves, "making it cohere, even before we talk about it, by the infinite paradigm of difference, subjecting it from the outset to a basic typology, to an evaluation…" (Barthes/Miller, 1991).

Without negative analogies we're just doing the *same thing* over and over – we have a set of solved problems and the business of science is to recognize how new phenomena fit within these solved problems, but taking into account the negative analogies, we're changing – adapting our categories, extending and limiting them. Below I present a brief sketch of research and questions concerning negative analogies – that is, the places where analogies are not correct but the analogy overall is still accepted and the base is understood within this new cognitive model. These analogies shift our understanding not only of the target – because it is placed into a new, unexpected schema – but also the base of the analogy, because elements that seemed inherent to that base and fundamental to the schema become tangential.

At the time that I first came across these readings by Barthes and Saussure, I had just left a condensed matter laboratory, where I spent most of my time writing computer programs to interpret data on the structures of sandpiles (Atkins, et al. 2001). Much of programming – at least in the sciences – involves taking a piece of code that is in some fundamental way the code that you need (usually from *Numerical Recipes in C*), but not quite, and modifying it. The original programs often bear very little resemblance to the final program – but the core of the idea remains. How do programmers choose a particular structure for their programs? How do they analyze the strengths of these particular lines of code, know what to modify and what to keep?

Rachel Scherr, as part of her doctoral work on relativity, created a set of tutorials that leads students to arrive at the relativity of simultaneity. The context of the tutorial is two relativisitcally related reference frames, each of which is observing a single tape player in a scenario that is contrived to give students the following options: either the tape player is seen by one observer to play and another observer to remain off, or simultaneity is relative. As Scherr (conversation) claims: "If you have to choose, I'd much rather give up simultaneity than allow the tape player to both play *and* not play." It is this determining of what is essential that lies at the heart of much of scientific discovery – do we "give up" simultaneity in order to preserve causality? Which is more fundamental to our science if we can't have both? Do we allow popes to be bachelors or do we refine our definition of bachelor? Which is the more primary? Are quasi-crystals crystals? Are viruses organisms?

Negative analogies in physics

In "Analogy as the Central Motor of Discovery in Physics," a talk given by Hofstadter at the Ohio State University (2003), Hofstadter argues that analogies are a driving mechanism for discovery in science. He details the progression of ideas from a literal field with hills and valleys, to assigning the gravitational potential to every point in space – a scalar field. And from there scientists tried to draw the analogy from the gravitational field to the electric field, and eventually ran into a problem with magnetism: what could they “give up” or “tweak” about the scalar potential and still maintain its more important underlying structure (as a thing you differentiate to find the force)? – the answer was to recast the scalar field as a vector field. Much of science consists of trying to extend a known law into a new area where it was not meant to be applied – drawing analogies between pieces and “tweaking” a few things. These tweaks – that the electric field is like the gravitational field but different, or that in relativistic scenarios we must abandon simultaneity – are the differénce introduced by Saussure and expanded upon by Barthes. They argue that in drawing an analogy between the two fields, the relevance is not in the ways in which the two are similar – that overarching schema in which both are understood – but the places where they are different. This idea has been termed the “negative analogy” in the philosophy of science.

Negative analogies as a caveat

The negative analogy – the pieces of the base that do not transfer to the target – was first introduced by Hesse in 1966, but has not been widely recognized since. One reference can be found in “The Metaphorical Transfer of Models” by P.B. Sloep (1997). In this article, Darwin’s natural selection is seen as an analogy to the selective breeding of gardeners, and the negative analogies are as crucial as the positive analogies:

> …natural selection and artificial selection differ too. It is not for nothing that we said in the above ‘it looks *as if* someone selected them.’ While the proto-fantails were hand-picked by their breeders, in natural populations selection results from natural processes such as the struggle for existence. Here we have a difference or a *negative analogy*, as Hesse would call it: a human selecting agent versus natural processes. Negative analogies are as essential an ingredient of metaphorical transfer as positive analogies. A metaphor without them would cease to be a metaphor – i.e. an explicitly non-literal referring term – it would be the ‘real thing’ – i.e. a literal referring term – and we would end up with an identity

> relation rather than one of analogy. At the same time, negative analogies embody the limitations of a metaphor… if negative analogies are not recognized for what they are, mistaken inferences loom large.

It is true that negative analogies are a crucial element of science – but not solely because "if not recognized for what they are, mistaken inferences loom large." I don't want to place a caveat *against* negative analogies – there is the danger in reading this passage and believing negative analogies to be no more than pitfalls, limitations and places for error. This interpretation of negative analogies is widespread (i.e., Gentner and Gentner, 1983; Clement, 1987; and Lulis, Evens and Michael, 2004). David Brookes (2003, 2004) has argued that scientists are inconsistent with their approaches to problems: speaking of quantum mechanics in the Bohmian sense one moment and then the Schrodinger model the next. We talk about heat as though it is a fluid, but treat it mathematically as a process. This is cited as a concern, but I believe that many and conflicting representations of phenomena may be a strength if appreciated and understood for what they are.

Meaning arises in these negative analogies – the places where the representations are not accurate (can lead to incorrect predictions) and where they conflict – and this may be a strength of analogies. Meaning comes not only from the patterns and similarities between things but also the differences. It is in the tweaks – the fact that the magnetic field is a vector, that heat seems like a fluid and isn't, that we think of quantum mechanics in a Bohmian sense but also don't – that we find the science.

Directions for future research regarding analogies and mind

The changing schema

A direction for future research is to investigate what happens to the *schemas* through the use of analogy? How does the analogy change the understanding not only of the target, but also of the schema for which the base is a representation? For instances in which the schema is "tweaked" in constructing analogies, how do we determine when it is a "variation on a theme" and when it is a new theme altogether? Is this a continuum or is there a clean delineation between including the target in an established and stable schema and changing that schema slightly to accommodate the target?

Conceptual blending

A possible extension of these questions – concerning how the negative analogies between the target and the base affect our understanding of the schema that applies – relates to work on conceptual blending. Fauconnier and Turner (1994) note the following regarding conceptual blending (also known as conceptual integration):

- Mental spaces are small conceptual packets constructed as we think and talk, for purposes of local understanding and action. They are interconnected, and can be modified as thought and discourse unfold.
- In blending, structure from two input spaces is projected to a third space (the "blend").
- The blend inherits partial structure from the input spaces, and has emergent structure of its own.

These ideas are related to and could possibly provide a partial answer to the questions raised above regarding how our schemas change to accommodate new phenomena. Constructed bases (as opposed to recalled ones) may arise from the piecing together of schemas that are not typically associated with one another.

The implications of technology on science

Another interesting question is to explore the connection between technology and theory. One interesting implication from Otis' research is that not only does our science create new technology, but technology creates new science: not only because of the technological affordances, but the introduction of new schemas and new language. Scientists had no accurate way of envisioning the nervous system prior to the invention of the telegraph – they borrowed language from hydraulics but it was of limited use. There was no way of understanding the olfactory system prior to the scanning tunneling microscope – scientists spoke in terms of enzymes because that was the paradigm in other biological processes. Is this a rare phenomenon, or can most of our scientific theories and conceptual revolutions be, at least in part, attributed to changes in schemas that were brought about by new technologies?

Science in the absence of analogy

Related to this question are questions concerning systems for which there are no "good" analogies. In particular, I am interested in the way that quantum mechanics is taught and the way in which it is conceptualized. There are few, if any, systems that are analogous to quantum mechanics: most seemingly analogous systems incorporate a "hidden variables" component. What are the analogies that people use to understand quantum mechanics? What schemas do people tap into to understand and come to grips with this strange phenomenon? Above I suggested that quantum mechanics is perhaps not an analogy to physical phenomena but to mathematical ones. Although I later began to conceptualize probability amplitudes by comparing them to electromagnetic waves, it was initially an understanding of linear algebra that first informed and explained quantum mechanics. (My undergraduate professor for mathematical methods for physicists claimed that all of physics is linear algebra.) Of course, analogies from physical to mathematical systems beg the question as to whether or not mathematics is understood via analogies to the physical world. Lakoff and Nunez, in the book *Where Mathematics Comes From*, argue that math, far from being an abstract and objective field, is intimately tied to analogies to the physical world:

> When you think about it, it seems obvious: The only mathematical ideas that human beings can have are ideas that the human brain allows. We know a lot about what human ideas are like from research in Cognitive Science. Most ideas are unconscious, and that is no less true of mathematical ideas. Abstract ideas, for the most part, arise via conceptual metaphor-a mechanism for projecting embodied (that is, sensory-motor) reasoning to abstract reasoning.
>
> This book argues that conceptual metaphor plays a central, defining role in mathematical ideas within the cognitive unconscious – from arithmetic and algebra to sets and logic to infinity in all of its forms. (Lakoff and Nunez, 2001 preface)

Embodied cognition and analogies in science

In the above passage is a final question for generated analogies in science – that of embodied cognition. The idea of embodied cognition is that "human ideas are, to a large extent, grounded in sensory-motor experience. Abstract human ideas make use of precisely formulatable cognitive mechanisms such as conceptual metaphors that import modes of reasoning from sensory-motor experience." (Lakoff and Nunez, 2001, xxi). That is, when you ask someone what a triangle is, the definition they immediately turn to is not mathematical formalism, but a process by which you draw that triangle – often involving gestures.

For abstract concepts like "what is truth?" Barsalou and Wiemer-Hastings (2004) have shown that definitions often involve scenarios: "It's when you…". The relationship between analogies, categories, gesture and embodied cognition is interesting. The schemas that I have argued as fundamental are abstractions from concrete, embodied experience and analogies between concrete experiences, I have argued, are mediated by this abstract schema. Perhaps at some deeper level, these schemas are represented as sensory-motor patterns, which are in turn associated with objects existing in the world, and the choice of base for our analogies may be related to this sensory-motor experience. This relationship has not been explored in this thesis but is a logical extension of this work.

Analogies as a tool for exploring categorization

Having established that analogies are assertions of categorization, this research can inform many of the open questions in categorization. Current questions involve the structure of categories and distinctions between taxonomic categories and other forms of categories. The vast majority of investigations of the mind's organization start with a prompt for the participants of the study, such as asking for a list of trees, "things to take from a house during a fire," or even to guess at a professor's judgment of the typicality of a certain type of bird. Such studies miss the everyday acts of categorization that happen without awareness or effort. Students in a class discussing why this sky is blue came up with many different analogies: the sky is like a bubble, a prism, or a neon sign. But when these students were informed by the instructor that their analogies all were ways of getting color from a colorless thing, they expressed surprise. And had they been given the prompt, "what are ways to get color from colorless things," it is not clear that the analogies – or members of this category – would have been identical to the analogies they constructed without such a prompt. This suggests an alternative and less "invasive" or contrived manner of arriving at the organization of concepts by studying spontaneously-generated analogies.

Network theory and analogy

A final direction for this research is to use analogies as a means of understanding the cognitive map as a conceptual network. Lexical maps have been constructed (Fellbaum, 2003 and others), that relate our semantic terms in a network – thesaurus-like or internet-like in its construction. In these, words are nodes and linked to one another, and the activation of a node activates those that are linked to it. A similar construction has been considered for the linking and activtion of concepts (Collins and Loftus, 1975) – but this would beg the question of what is *a* node? As Hofstadter notes (2001) a concept can be quite large and particular, as in "a strange shape that the electrical charge may take that cannot be then be solved from first principles." And yet our large concepts seem to be pieced together from smaller schemas. How are these concepts and schemas organized in the mind? What size pieces are fundamental – or is that question even meaningful?

Below I turn to questions for the implications of this research on instruction.

Directions for future research on the implications for instruction

While I make claims about *what* analogies assert and the cognitive mechanisms involved, I have not come to any conclusions about *how* this happens. How does Miranda make this incredible leap from seeing a cup of water to thinking of a cat in a basket – why were these schemas activated for her? Of course the experience with the schemas involved was necessary, just as Luca Turin had to know about scanning electron microscopes before he could draw an analogy between this and scent, but what habits of mind and what structure of education can encourage this kind of creative re-categorization of concepts?

Questions regarding student epistemology

As a first pass at a partial answer to this question, I would like to suggest that students must know that they *should* generate analogies as part of what it means to do science. That is, it requires a change of students' epistemological stance towards science. This is an argument that was discussed in the chapter regarding implications for instruction. But it leaves open the question as to how to change student epistemologies. I have found – anecdotally – that telling students to use analogies often results in superficial analogies: temperature equilibrating is analogized to a chameleon changing color, or an electrical circuit is imagined to be like a cow's digestive tract (both analogies have occurred in Maryland physics classrooms). These students, when *told* to draw an analogy, are not choosing a story that makes sense to them could apply here. I don't quite know what they're doing with the analogies they construct – and they don't quite know why I am asking them to construct. In trying to understand these moments, I've wondered if these strange analogies can be understood in the context of a teaching philosophy from *The Inner Game of Tennis* (Gallwey, 1997). This sports psychology book argues that too explicit of instruction can (in the context of tennis) lead to unnatural and unfavorable results; telling someone where the ball should hit the racket, say, decontextualizes what should be one piece of an integrated whole. So perhaps an explicit focus on analogies prevents the natural evolution of an analogy – as response to an unexpected result and stemming from activated schemas. This is just speculation at this point. But it suggests a possible starting point for how we can design curriculum and learning spaces in a way that encourages analogy generation.

The design of learning environments

An additional, related question is whether the use of analogy (or lack thereof) a question of expectations, epistemology, or is it a domain-general ability? That is, in designing our learning environments to encourage analogy, should we be addressing students' ideas about what kind of knowledge they should bring to bear? Should we try to encourage the activation of multiple, contradictory schemas? Or is it a general facility with or predisposition towards analogies – does a facility with analogies in, say, literature, translate to an increased use of analogy in science?

Concluding thoughts

Before my work on analogies, I was involved in curriculum development surrounding wave phenomena. In watching students interact with this and similar curricula I was dismayed that, though they eventually understood the concepts that the curriculum was addressing, the students never approached *new* topics in a creative, scientific, sophisticated way. They were better *engineers* in the end – they could apply algorithms that the curriculum had carefully developed, but they weren't better *scientists*. It seemed they were at a loss when learning new topics and constructing novel ideas. A student came to class one day wearing a t-shirt from a punk rock band. It read: *You can lead a man to reason, but you can't make him think*. I wanted my work to address this. To begin to think of the classroom as more than a place to lead our students to reason, but as a place where deep scientific thinking occurs. I think this thesis is a start. It highlights one significant component of scientific thinking – analogy. I claim that analogy is the ability to consider alternative models, deliberately overriding cognitive knee-jerk reactions to phenomena by tapping into alternative models and representing the categories that these models construct.

In *Drawing on the Right Side of the Brain* (Edwards, 1989), readers are instructed to turn a Picasso sketch upside down and then try to reproduce the upside-down drawing. Results are phenomenal – even people who have trouble drawing stick figures are often create remarkably accurate reproductions. We cannot help but see a nose when a right-side-up nose is drawn before us, but by turning it over we can begin to see the lines and curves as lines and curves and override our assumptions about how noses are shaped or where eyes go. Analogies allow us to do a similar thing – they demand that we turn the pictures upside down and dislodge the cognitive models that we were applying. Analogies allow us to stop seeing the nose as a nose – we stop seeing the cup as a cup and instead pay attention to the way in which it as a basket, how metal is a set of stepping-stones and quantum mechanics problems are like Bugs Bunny's ears.

Appendix A

Transcript 1

This transcript is from an undergraduate course in physics, Physics 115: Inquiry into Physical Science. The students have been investigating electrical phenomena using Styrofoam (an insulator that charges easily when rubbed with wool) and a metal pie plate (a conductor). They began their study of charges using transparent “scotch” tape: when two pieces of tape are put one on top of the other and peeled from a table top, they each get an excess of different types of electrical charge (positive and negative) which the students have termed “top” and “bottom.” Prior to the discussion below, the students have been asked why Styrofoam and metal have such different electrical properties and have worked in small groups to address this question. They are now presenting their ideas to the rest of the class:

Hana: I kind of see the charge in metal as like, fish in a fish bowl? Like they never really stop moving, they’re always kind of floating around wherever they kind of feel like going and that’s just how I see it in my head, like them always moving around. And I don’t know what hap- I don’t know how to describe it really I don’t really know what happens once another charge is brought closer then.

Instructor: Does this make sense to you then?

Hana: Yeah.

Instructor: So this is – so this is like two kinds of fish. [Hana: Yeah.] And in metal they can move around. They’re kind of stuck inside the bowl, but within the bowl they can move around.

Hana: But I also think that they can leave the bowl at some point because—

Instructor: Well we get shocked right? I mean that’s—okay. I’m a charge I’m in the pie plate, what am I doin’? [Hana: Movin’.] Movin’ I’m movin’.

Kelli: That same idea I was thinking except more like ping pong balls that bounce all around and that’s why if there’s top and bottom charges they're moving around a lot and they're kind of attracting and repelling and attracting and repelling each other the tops and bottoms that go all over the place—but once the extra bottom charge is added it's almost trying to like reneutralize itself and the tops are attracting to the extra bottoms. And then they're trying to kick out the other extra bottoms so they can get back into their whole little [Student: Balance.] balance. Bouncing around.

Instructor: So this- I think what you're offering is an explanation of why I get a shock. Is that—am I wrong?

Kelli: No, you're not.

Instructor: So you're, you're thinking that if there's extra bottom charges in there it's like they want to get out because it's unbalanced. And it has to do with them just kind of all bouncing around like ping-pong balls if you've watched the lottery drawing. Alright. Okay. Terianna?

Terianna: So- are you saying that they—so she's saying—are you saying that there's a little [inaudible] that charge moves throughout the pie plate?

Kelli: I think I think so.

Instructor: Okay—so are you agreeing with that picture that I drew down there—okay so it really is going with always moving.

Christie: We were thinking that—like they were saying that in metal it's always moving, so if it's always moving it has more room to move and that would mean to say that the molecules are less tightly packed together or less dense and we were thinking of Styrofoam as more dense than—I'm just trying to figure out first if that's right and how it relates.

Lea: I don't agree with you saying that the Styrofoam is more dense because, so that's why the charges get caught up in it because like—[inaudible] pan is more dense so they're able to slide across it like they can ice skate across the [inaudible] here. So that's why they move around more 'cause it's more dense so they can slide across it more and the Styrofoam is less dense and so they get stuck in it. Like so they can't move as much.

Instructor: Lea I want to add—I think you're sort of what I when I hear you talk I'm thinking of like, pouring water into a sponge versus pouring water onto a hard surface. [Lea: Yeah.] Like this sponge is actually less dense and there's room for it to absorb the water and the you know if you pour it onto something hard there's no room for it to absorb. But Christie—I mean this is an interesting thing you guys are both thinking that density is important but one of you is thinking that more density means one thing and one of you is thinking more density means the other thing. Is that is that—am I right? [Christie: Yeah.]

Lea: Yeah, I have a question about the sponge- like the charge instead of being able to move freely past it and they get kind of stuck in it like water and the pan is like the countertop and you pour water on it it's going to slide all around and stuff but the charges can move more freely on the pan there's probably– I think that maybe this has more charge in it because there's more places for the charge to leave than the pan does, but there's more potential charge in this than the pie pan. [Unknown: Like it can hold more charge.] Yeah it can hold more charge but they can't move around as freely.

Student: So you're saying the charge is like [inaudible] out on the metal? Like on the outside?

Lea: Yes.

Student: It's like made up of it—like, they're electrons.

Lea: Yeah—like I don't know but it's like definitely a lot smoother. They're, they're denser they can move around more freely like.

Instructor: Hana?

Hana: As, as far as like air is concerned—air moves from high pressure areas to low pressure areas and so like I don't know I don't know if that's like a completely separate idea?

Instructor: But you're offering this as a kind of "maybe this explains why there's charge pressure—there's high charge pressure and low charge pressure."

Hana: Kind of but I know that I know that high—like when you're in the shower and the shower doors close and it gets all steamy as soon you open the door you feel like the cold air feels like it's rushing in? Because inside the shower it's low pressure and then once the door opens all that high pressure kind of like rolls right into the into the low pressure area.

Instructor: I just want to- I know- there are people here- I just want to clarify Lea and Hana your question your question was is charge moving on the surface as opposed to moving inside and so this would be like are the fish swimming in the middle of the fishbowl or are they somehow sort of stuck on the edge of the fishbowl. Is that sort of what you're – [yeah I disagree with her idea] okay.

Lea: I really don’t know I was just trying to—

Lydia: I was going to say I think the pie plate is more dense but I do think that it’s inside not outside because if there’s more space to travel then the molecules can’t get from one space to another easily but it’s all [inaudible].

Instructor: Oh so it’s like stepping stones [Lydia: Kind of.] like in the Styrofoam it’s really far to the next stepping stone so it’s like can’t get there I’m stuck here. [Lydia: Right] but in the metal the stones are really close together so I can kind of walk across. [Lydia: Yeah.]

Appendix B

Transcript 2

The following analogy is from a 5th grade classroom in a rural Maryland public school. In this transcript, the students have been visited by the science resource teacher and posed the following question (NASA, 1999): a cup full of water is inverted on a cookie tray and the tray is rapidly pulled out from underneath the cup (see Fig. 2). What happens to the cup-water system? The students will later observe that the water does not leave the cup as it falls to the ground—the cup falls at the same rate as the water and the water will only spill out once it reaches the ground.

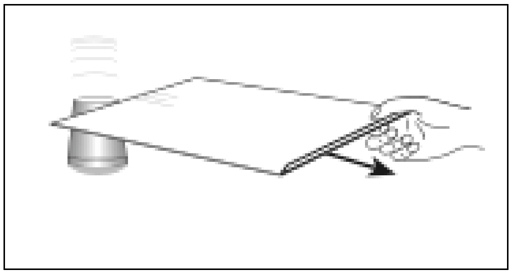

Fig. 2: The Experiment: A tray pulled out from under a cup

Teacher: So you're predicting as I slide the cup off it's also going to go all over the tray, too.

Gabrielle: Like, it'll spread and then it will fall.

Teacher: It's- the water is going to spread and then it's going to fall down. Okay now I might come back to some of these ideas that you've had but let's see what some – I see a lot of other hands up. Um, Miranda?

Miranda: I predict that when it falls off it's going to stay in the cup until it gets down to the floor and then it'll splash.

Teacher: So you have a prediction that when I slide it off of the tray the water is going to stay in the cup. Now that's very different from what they're saying.

Miranda: 'Cause at home when I have like something in a basket and when I go like that real quick it stays in. So when – and when I pull it down like this like upside down on the way down it stays in until it gets to the bottom and then it comes out.

Teacher: So you're using now this example of something that you've done at home where you have an object in a bucket- or a basket- you said and what do you do? You—

Miranda: I go like this and then I pull it down and it stays at the top until I stop and then it comes out.

Teacher: So you swing this – what's in the basket? What object is in the basket?

Miranda: Sometimes I put like like a little toy cat that I'm playing "roller-coaster" with and put it in there and I pull it down [Teacher: Is that right?] and it stays in the back until I stop and then it comes out.

Teacher: So you swing this basket like this—do you, do you do it quickly or slowly? Or.

Miranda: I do it quickly like that.

Teacher: You do it like that and then pull it down [Miranda: Mm hmm.] and the cat stays in the basket [Miranda: Until I stop.] even when you have it upside down like this and pulling it down and when you stop

Miranda: It comes out.

Teacher: The cat comes out. Okay now has anybody else- want, can relate to this also? Looks like a lot of you can. Let's hear some of your ideas. Let me come over to – thank you Alyssa.

Alyssa: Um. Um what she's also talking about it's the air- it's like pushing the cat up against the the bottom of the basket which is holding it back from going out.

Teacher: Okay, so now you're- and this is where I was going to go, too, after what you said is, um, explain how the cat would stay in there and you're thinking is, Alyssa, is that the air—

Alyssa: —is pushing the cat towards the bottom.

Teacher: Okay, so so the air is pushing the cat towards the bottom of the basket keeping it inside the basket. When—now when I'm thinking of that, and maybe some of the others can help me with this, but I can picture the air when you pull it down being forced up against the cat—is that what you're talking about? Miranda?

Miranda: And it'll be the same thing with the water the air will push the water up until it falls down and then it will go everywhere. Because when it comes down the air is pushing upwards and [it keeps/I keep?] the water in there- because I've also done that in the bathtub when you've got your cup, I'll like I'll fill it with water put my hand

and drop it the water stays in until it hits the bathtub and then it goes everywhere.

Teacher: So your thinking is then this air is keeping the water inside the cup. Alyssa your thinking is that the air keeps the cat inside that basket that Miranda was describing. You're shaking your head "no" Gabrielle?

Gabrielle: Yeah because like when you put like a toy cat in a basket, that's only that one small thing but you now have a cup full of water, so how would the air keep it up if the cup is already full?

Teacher: I'm I'm not sure I follow what you just described, you said the cat is just a small [Gabrielle: Toy.] toy so—

Gabrielle: So and it's only one thing.

Teacher: Okay wait a minute—so the cat's only one thing but the water is—

Gabrielle: So you you're going to have the cup full so how would the air like keep it up if the cup is full?

Teacher: Oh- so her did you hear what she just said Miranda? [Miranda: Mm hmm.] She's saying that if I fill the cup- if I fill this cup- you, you're saying if I fill the cup to the very top there's no room for the air to keep the water in there. Okay well, I I have a question for you then Gabrielle—what's your prediction if I fill this cup all the way to the top, turn it over, slide the cup off what will the water do? I filled it all the way to the top, turned it over.

Gabrielle: How far do you now have the cup up?

Teacher: How far in the air?

Gabrielle: No to the edge.

Teacher: Oh to the edge? I – I was probably, I don't know, as close to the edge as I can get it.

Gabrielle: Well, I think it's

Teacher: And then I'll do this. Or—

Gabrielle: Oh my prediction is that um, what Alexandra said that the cup slides off then it'll just go down—

Teacher: Okay so you're still with your original prediction where you think the water is going to go everywhere.

Gabrielle: Yeah but it's—I think it, what it's going to do, is the cup'll fall off and some of the water will splash into the bucket. I don't think it's going to go—

Teacher: I'm sorry say that one more time it's going to do what? It's going to—

Gabrielle: I think when the cup slides off that the water will go down to the bucket and make a splash.

Teacher: So it's not going to stay in the cup like Miranda's predicting.

Gabrielle: Right.

Teacher: Okay what about if I only fill the cup up halfway? Now we’ve got room for this idea we’ve got room for the air. What do you predict will happen? And I slide it off of there. Maybe I’ll just push it off of there like that. [Teacher pushes empty cup off and it tumbles in the air on its way down.]

Gabrielle: Well, see, the cup like turned a little bit, it like went side a little bit so um.

Teacher: Well what do you predict the water will do if I only fill it half way? Is it going to do the same thing as if I fill it all the way?

Gabrielle: Um— yes it’s going to do the same thing.

Teacher: It’s going to do the same thing. [Gabrielle: Yes.] So you don’t think air has anything to do with it then? Keeping the water in the cup?

Gabrielle: No because like when you’re turning the basket then you kind of keep it straight when you’re holding the handle like that. When you drop the cup the cup can just zoom all directions too.

Teacher: Oh I see what you’re saying—when you’re holding the handle on a on a basket or a bucket you’re kind of keeping—

Gabrielle: You’re keeping it straight.

Teacher: But your thinking is when it falls like this it could tumble—it’s going to move—there could be some movement in the cup.

Gabrielle: It’ll turn sideways.

Teacher: It could turn sideways like that. And that would make a difference. Okay let’s get – a lot of you have been very patient. Cody?

Cody: Um because when I was um having bucket full of water and I swing it around and then when I throw it the bucket of water still stays in there- the water, and

Teacher: You’re going around throwing buckets of water?

Cody: Yeah-they’re made out of plastic.

Teacher: When you when you swing that bucket of water around—

Cody: Yeah and then when I throw it the bucket of water still stays until it hits something.

Teacher: So the water stays inside the bucket even when you when you’ve let it go the water stays inside of there. Well what do you predict will happen when I do this with the cup of water?

Cody: It will turn before it hits.

Teacher: What will turn, the cup?

Cody: It- it would, the water would go out a little bit and then it would splash.

Teacher: When I do this, what will the water do?

Cody: Um the water – if you pushed it hard enough the water would go out flat a little bit and then fall.

Teacher: So if I push it hard enough—well that might not be a good example. But if I push it hard enough you’re saying that water will stay there for a moment- it will stay flat is what you said- and then what would happen?

Cody: Then it will fall down.

Teacher: And then the water’s going to fall down. Out of the cup? The water will fall out of the cup? Or—

Cody: The water would splash out before it- after it gets out of the cup and then fall down.

Teacher: So it’s going to it’s going to go like this, water’s going to stay flat for a split second—

Cody: And then the cup and the water will fall down.

Teacher: Will the water stay in the cup as it’s falling? The water’s going to fall out of the cup. But you just said that when you swing the bucket, though, that the water stays in there.

Cody: But when you push on the flat then um? It’ll turn around—

Teacher: So we’re still thinking about this pushing it off of here, though—that

Cody: [Inaudible.]

Teacher: So it forces the cup to to uh turn. Isaac?

Isaac: Um I pre- I don’t- um I agree with Miranda but I don’t think air has anything to do with it. Because um yesterday at Trick-at-Treat I had like a bunch of candy and I swung it around that’s like when I was bored and stuff—

Teacher: In your bag?

Isaac: Yeah. And none of the candy came out. I like kept on swinging it and also when me and Johnny play monopoly there’s like this little hat that we play with when we roll the dice [Teacher: Mmm hmm.] and like we always put the dice in and flip it back to each other with the dice in it and we always catch it and it stays and the dice stay in.

Teacher: And you’re in agreement with Miranda that the water will stay in the cup however you don’t think air has anything to do with it.

Isaac: No.

Teacher: Have you given any thoughts as to why the water will stay in the cup or what what uh what will cause the water to stay in there?

Isaac: I just predict that cause of experiments…

[a few minutes of conversation regarding what happens before the cup falls]

Teacher: …Alexandra?

Alexandra: Um when Miranda said how when she dropped the cat in a um basket- I've done that with um my Easter candy but with more candy in it and when I turned it over when I got up here and it dropped it all went everywhere.

Teacher: But when you were swinging it, it didn't fall out until you got up here and then stopped and then it all fell out.

[Alexandra nods.]

Teacher: Isaac?

Isaac: I don't really agree with Dillon because the only reason it'll fall out is, um, if the board is crooked and the cup is straight and also if the cup has a crack in it.

Teacher: The cup is pretty good- I mean it doesn't have any cracks in it, and although the cookie tray it looks a little… pretty straight. It's hard for you to tell I know. Um. Let me just summarize, really, for my own benefit and perhaps for yours as well. And then we'll come to you Gabrielle.

Teacher: We have a couple of different ideas. At least three I think. We have Dillon and his group who are thinking that – or I'm sorry predicting – that when I turn the cup over the water is going to go everywhere. We have another group, I think it might be I would call the Amanda group who is predicting that water's going to stay that it will stay in the cup even when I turn it over and the water will stay in the cup when I push it off of the tray. Ok? And then we have some of you- Alexandra who had originally predicted and Gabrielle that water is going to fall out of the cup when I push it off of the tray. Are there any other ideas, other than those three?

Ethan: Are we going to be able to try it out.

Teacher: We are going to be able to try it out.

Student 1: Today?

Teacher: Today.

Student 2: We always do it fifteen minutes before we're done.

Teacher: Well now I want to hear your talking and your thinking about this now. Gabrielle, you had something to share go ahead.

Gabrielle: I was going to say that I think the water will fall out once it leaves the board.

Teacher: Soon as I do this the water's going to.

Gabrielle: Yeah because see when you put the board

Teacher: The Cookie Tray?

Gabrielle: Yeah.

Teacher: Please use the correct scientific terms, ok, this is a "Cookie Tray." I'm just kidding.

Gabrielle: When you put the cup on the tray and then when you go to slide it off some, some of it like that- not all of it comes off at once. Some of it comes off a little bit so I think when, when a little bit is off the water will just fall down because there's a crack.

Teacher: Oh. Let, let me repeat what I heard you say and then I'll get to you Alexandra. It gets to this point some of the water is going to come out.

Gabrielle: Yeah because, um, that part has a gap in it so I think the water's going to fall out.

Teacher: Do you see what she's talking about you have this little bit?

Appendix C

Transcript 3

The first transcript below is from a research group meeting of the Physics Education Research Group. Paul, a graduate student, is interested in authentic classroom activities and is discussing his definition of authentic. Key to this definition is that authenticity is a property not only of the activity but also but also in the way that the students relate to that activity and the coherence of this to the scientific community of practice (that is, do the students know what they're doing? Would scientists agree?). This is at odds with definitions of 'authentic" activities that situate authenticity as a property of the curriculum itself. The transcript begins with David summarizing the concerns with respect to prior definitions of authentic.

David: It's not a responsive definition of authentic. Authentic is defined pre-experience. And so what your [Paul's] sense is what's going to be authentic is about watching the student and and what is authentic for this group—may be different from what's authentic science for *this* group. And you don't like defining authenticity in a way that isn't responsive. So the content isn't responsive but also the sense of what is authentic isn't responsive.
Rachel: So ontologically authenticity is like fun. Which would be—
David: Oh that's great.
Andy: Oh that is beautiful!
[Laughter.]
Rachel: —because you can—
David: There's an analogy for you Leslie. [Leslie: Yeah.] Are you taping this? [Leslie: It's being taped.] Alright.
Andy: – it emerges from an activity but it's really ultimately lives inside—
Rachel: Right and I mean you could say—I mean you couldn't look at a thing on paper and declare that it was fun until you could see people do it and see them have fun.
David: And it may be fun for some people and not fun for other people.

Andy: You could – an experienced teacher could make guesses about what's more likely to result in fun blah blah blah.

Rachel: Sure, sure. But really ultimately you don't know until after [inaudible].

David: Or anyone—what what my kids think of as fun might not be the same as what Rachel thinks of as fun [trails off]. I'm sorry I'm just struck I'm I'm thinking of Leslie's stuff for a moment—what's cool is how powerful it is to connect that question—how powerful it is what you just did. That when you say it's like "fun" boy that brings in a lot of stuff to help me understand the kind of claim that that we're batting around.

[Undiscernable/is that right? Comments.]

Paul: Ten minutes—we could break early?

Leslie: Is there a community of fun practice?

[Laughter.]

Rachel: Or norms? [Laughter.]

Leslie: Like with the community of practice the scientist is someone who's outside deciding whether or not it was science but with fun there isn't – so it's a negative analogy—but with a community... yeah there's no community of practice.

David: I don't know what you mean— there's no authentic community of practice?

Leslie: You only have to ask a person who's having fun if they're having fun. But this (definition of authenticity) implies that you have to ask the scientists whether they're doing science.

David: Ahhh—right. Gotcha.

Andy: Not only does it have to be meaningful it has to be meaningful in the right way—but— yeah I'm having fun but it's – you know—low-brow fun instead of highbrow fun. Guffaw guffaw! Gotcha.

[Laughter.]

David: So can we patch that? Is there, is there another

Matty: [Indiscernible. Overlap—like.]

Rachel: Good clean fun?

[Laughter.]

Matty: Like I'm wondering you know—what can be considered "fun" by a group of people you know there's like overlap like a culture who considers certain kinds of things fun and there's like overlap between the adult (?) individuals—same with like if you consider that like the community of fun practice, like the community of science, I think individually everyone would consider...

Leslie: I have a multiple analogy if that’s okay? I’m thinking it’s more like worship—like, you know if you’re worshipping but a religion is going to also decide if what you did was worship.

Andy: Oooh.

David: Right. Right that’s good.

Andy: It’s gotta pass both tests. That is good. Good clean fun works, too. You decide if it’s fun, *I* decide if it’s good and clean!

[Laughter.]

Leslie: Or pornography?

[Laughter.]

David: Paul wants to stop. We’re done.

Appendix D

Transcript 4

The following transcript is from a third grade classroom in a suburban Maryland public school. In this classroom, the teacher has asked the students: if you are running with a beanbag and want it to fall on an *X*, should you release it before, when, or after you reach the *X*? This question is particularly interesting because all three answers are plausible and can be argued with analogies to past experiences.

Camille: I think— I think that you're gonna drop it before.

Teacher: Why?

Camille: Because it— you just keep on running and then— I don't know.

Teacher: Why would it not drop straight down?

Camille: Um— I'm just thinking that maybe if you're running it might just go back, back— I mean forward when—

Teacher: Because I am running? And it will go forward with me because I'm running?

Camille: Yeah.

Teacher: How many people think it will be forward— it will go forward. I need to drop it like somewhere around here. Way before hand. Adam, that's what you think? When you back up, can you help me please.

Adam: Um, I think, because one of Isaac Newton's rule of physics is a body in motions tend to stay— a body in motion tends to stay in motion until stopped, or something like that. And that, um— when you're running and you let go, if you let go before, it will— it will instead of going straight down, it will go um— it will go in front because it's not stopped yet. But when it hits the ground, because there is friction on the ground— there is more friction on the ground than in the air it will get stopped and land somewhere around there.

Teacher: You had a really um— a really good idea that I want you to really kind of explain it to some people that may not understand your law of motion and may not understand the word friction. So I need you to try to restate your idea, and try to think about not even using that law as an— as an example, but trying to just explain it to someone using your experiences— see if you can use it that way. Explain to— like you're explaining to a kindergartner. They're not going to be able to understand that law.

Adam: Like um—if—like if something—if you're riding your bike, um—it's in motion. And you're going to keep going until you get stopped by like— um, a rock or something. And, and—or going uphill. And so if you're on a bike, and you get—you can get stopped by something else, like a rock or something.

Teacher: So if we're thinking of your analogy to a bike, or your explanation with a bike, what's stopping it, and this is—

Adam: Um, no. Well, in the situation of dropping the beanbag. Like, um, it's thing is the ground, and because the beanbag is running against the ground, um— it's getting slower. Because like the beanbag is um— getting— I don't know how to explain this.

Teacher: Well, I'm gonna ask you a question, I want you to think about it for a second, and then I am going to come back to you. Okay? I want you to think about whether you think the beanbag's in motion. Because you know I'm in motion: my body's moving, but is the beanbag in motion? I want you to think about that question and I'm going to come to you in just a minute. Okay. Um— Connor?

Connor: I would think the bean bag would—might fall behind where you want it to fall because when I put—when I played baseball—they always said don't throw the bat because it might hit the catcher and not one of the um person because we're using metal bats, and—so we drop it, you drop it and then you—. Well, when I drop it, it usually swings backwards; it wouldn't be behind the plate instead of the front of the plate.

Teacher: So you're saying you have to drop it like somewhere over there, right— in order to get it to fall over there?

Connor: Probably.

Teacher: Cause of baseball.

Connor: Yes.

Teacher: And you saw that it usually fell behind.

Connor: Yes.

Teacher: Why do you think it fell behind?

Connor: Well actually it didn't mostly. It got on the side or in front because— well because you're supposed to drop it because you don't need a bat while you're running the bases. Once you drop it, I'm just thinking also, what Adam is— well a bus— well if you were on a bus and you had uh, this little leaf that you found, and the window was open, and you drop it, it will go— it'll be going backwards.

Lauren: That's because—

Teacher: That's okay, you can interrupt him if you want to talk about his idea.

Connor: It might go backwards.

Lauren: Because I think that's cause— you're talking about a leaf that's falling? That's because the— it's sort of— the bus is going back, so it's making like the air move. And the leaves are really, really light, so the reason they are going backward is because—. Um, well it's going so fast— a bus is like going so fast that it's probably making the air go that way. So that way the leaves are going that way.

[Many talking in disagreement.]

Connor: What if you did it with a rock? The same thing will probably happen with a rock. Because you are probably like a bus, that you make the air come— no one moves, don't you notice that um, objects like in cars or something— when you're going really fast on your bike that are— that um, you sometimes, [inaudible] and leaves your ankle on your back step and actually move.

Val: We're talking about a bean bag.

Teacher: What do you think is the key to that? His question is, is about the beanbag. So, um, since he's thinking that maybe the weight matters— what I am going to do is just pass this around, so you can touch it and think about that, um— if you think the weight matters, might help you to answer the question—

Kamran: Well, I think that—

Teacher: You can't interrupt somebody. You can share ideas, but you can't interrupt somebody as they're sharing. Okay you have to make sure he's finished. And when Connor's finished he'll let you know by calling on another person. Okay?

Connor: — but sometimes, yes I do believe that it might be about the weight also. So the heavier it is, probably it would land where you want it to. So say you had like a rock besides that beanbag, it would probably land where you wanted it to, because it would probably be heavier than the beanbag.

[Interruption as another teacher asks an unrelated question]

Teacher: Connor has this idea that the depend— it depends on how heavy the object is that we're dropped. So I passed around the bean bag. And um— that might be a good idea for Kamran to talk about, so Kamran is going to talk about that now. The weight and whether or not that matters.

Kamran: Yeah I think weight matters, because when Newton discovered gravity, gravity it’s, it’s has heavy enough to come straight down. If you’re moving and I’m not talking about beanbag, and I’m gonna put a pencil here and pretend that’s my mark. And then I ‘m going to move, but then I’m gonna drop down it and see what happens. But— like—

Teacher: I don’t want you test it. We’re talking about it first. We’re not going to test it, okay?

Kamran: Yeah, okay. But, but, I think that it, it, it matters on weight. A bus— you’re on a bus and the bus is the motion. Now if you drop a feather, that feather is going to go back. Also the bus in motion is producing like a kind of wind.

Teacher: Yeah, mmhmm.

Kamran: It’s giving air. Yeah. So the air is getting pushed into— it’s pushing the air back. Um— this is a drawing, this is the air, this is the bus. The bus is going— the air is going back. And if one of the windows, a feather comes the air is pushing it away.

Teacher: Mmhmm. Okay, okay.

Kamran: But, if you— cause you know a feather is— it, it, it goes with the air just simply its a light. That’s why— same with a leaf. A leaf is very light. And if you— a leaf falls [Inaudible.] goes to air. It doesn’t go, ‘leaf— boom.’ It doesn’t go like that.

Teacher: Okay, so—

Kamran: But a rock—

Teacher: Yeah—

Kamran: A rock is different, a rock has— it’s also like, it’s solid, but it’s not that a leaf isn’t solid, or a feather isn’t solid. A feather— but you have to— it’s very small, and it’s very like thin, so you kind of say like solid. But anything hollow, like if you have a paper box, that people would watch [Inaudible.]—

Teacher: Now we have a beanbag here. So since we have a beanbag, and you know that it’s not in a bus, we’re just driving— I mean we’re just running. What do you think is gonna happen?

Kamran: This—

Teacher: Cause you have that weight in your hand so you have a good idea.

Kamran: Um—. now this is hard, because somehow you can see it’s heavy, and somehow you can say it’s very light.

Kamran: It’s hard, that’s hard to say.

Teacher: So Cameron. So if you had to— get to share your idea right now what would it be. Where do you think you think you need to stand to get it to hit right there.

Kamran: I think you have to put it right there. Probably— we’ll it depends on what— here, you’re dropping it— you’re dropping it here, here?

Teacher: Right by my side— just drop it— I’m just dropping, not throwing. Just drop it.

Kamran: Yeah I think you have to be on, in order to— you have to be on this directly, and the middle of your shoe has to be on the line in order to make it drop—

Teacher: Okay and you— and you—

Kamran: Into it also, also it’s the most of minute [Inaudible.], if you’re going to see your shoe going on this [inaudible].

Teacher: It will go to the left.

Kamran: Yes.

Teacher: Um— Now you’re reason for having it hit right there, does that have something to do with the weight?

Kamran: Yeah, because the weight pulls it right down. If a tree— it’s heavy, and it’s heavier than all the leaves it has, so the leaves will make it fly.

[Laughter.]

Kamran: — flies here. And the tree, it will just go down.

Teacher: Okay, can you share— can you call on somebody that’s going to agree or disagree with you now.

Kamran: Um—Kathryn.

Kathryn: Um I agree with what you’re saying and all [Inaudible.]...

Teacher: I’m sorry, I can’t— I can’t go on cause I can’t hear you very well.

Kathryn: Um, uh— when you told me the first time, I didn’t really get it, so I [Inaudible.]—.

Teacher: That’s okay.

Kathryn: Can redo it?

Teacher: Um, don’t worry about that now.

Kathryn: Okay. I think that if you want it to land— well if you’re riding on a bus and you drop the rock down, it’s heavier than the wind, so I think it’ll go straight down.

Teacher: So you think that it needs to be heavier than the wind.

Kathryn: Yes, cause it’s going to go straight down. A beanbag and the rug—if it’s heavy and um— I would say you would have to be in the middle of the line, because [inaudible]— if you’re running it’ll go all the way behind you. But if it’s heavy enough, it’ll just drown you have to be in the middle of the line.

Teacher: Okay, I am going to ask you to stop right now.

Appendix E

Transcript 5

The following transcript follows two undergraduate physics majors working on a homework assignment on angular momentum in quantum mechanics. The students have had instruction on how to arrive at the quantum numbers *S* and *L* but are asked to find the square of the total angular momentum, J^2, which is $(S + L)^2$, or $S^2+2SL+L^2$. The students know how to find S^2 and L^2 but not $2SL$. They have a solution set from another student that provides the answer but not the steps to arrive at that answer.

Ben: That's what we're looking for in the first place. You don't think that's it?

Anselm: Well J^2 is L^2 plus S^2 plus 2SL. And SL is presumably the thing that could take on separate values within the probabilities.

Ben: It doesn't talk about J^2 though does it. [unclear] formula [unclear]. Although we should be able to figure it out cause it said the rules are the same whether you use spin or angular momentum.

Anselm: Yeah. That's fine if you know the rule. But we don't know what S times L really does. Cause SL doesn't really have a quantum number. Is it the square root of S and the square root of little-L, and then you take that times that plus one?

Ben: We should be able to figure this out from today's lecture.

Anselm: No you shouldn't.

Ben: He's gonna explain in detail probably Wednesday how you actually get to J.

Anselm: But see you're doing the wrong thing. Cause you're assuming that if you have the example, suppose there's a charge here, what's the electric field due to it? You can figure out, suppose you have Bugs Bunny, and he's charged, what's the electric field around his ears? All right. Because you have a simple example when they're both the same, you're not going to be able to figure out exactly what you're supposed to do when the rules weren't the same. Cause now it's fixed.

Ben: What other choice do we have?

Anselm: So like there's no like S, S+1, it's more like the square root of little-L times the square root of little-S maybe? I don't know.

Ben: Well what other choice do we have?

Anselm: Cry?

Ben: How else - Yeah. Okay, let's cry, I'll go cry. Now let's go on to B. ...I don't see anything that [I think's gonna help us]. And I feel like the book is just pathetic in this regard. It doesn't give us any help at all. I don't think it does, let me look back maybe there was something in it that helps. Combining spin and [angular momentum].

Anselm: Does your thing have the answers for this problem or not?

Ben: Yeah.

Anselm: So are there multiple J-squareds then?

Ben: Yes there are.

Anselm: Are they the ones we found?

Ben: No they're not.

Anselm: All right. What are they? Let's work from the answer.

Ben: Eight-ninths and one-ninth.

Anselm: That's the probabilities?

Ben: Uh-huh.

Anselm: Eight-ninths and one-ninth. All right. And what are—what are the values?

Ben: Fifteen whatevers in the, whatever we came up with. The values are the same.

Anselm: We didn't come up with that.

Ben: Yes we did.

Anselm: Well yeah we did.

Ben: These are the values.

Anselm: Yeah we did come up with the values. Um, but it's eight-ninths and one-ninth? And now you say

Ben: If you want to believe that.

Anselm: And now you say - You said at one point you had eight-ninths and one-ninth, where'd you get eight-ninths and one-ninth. What did you do.

Ben: All right, look at this look at this. If you take all the positives and add them together, you get eight-ninths.

Anselm: Oh, oh.

Ben: You take the negative, you get one-ninth.

Anselm: Yeah that's

Ben: But you're mixing apples and oranges. It's dumb!

Anselm: Yeah that's so messed up, yeah that's not the answer. If I just ignore the fact that I'm in the three-halves one-half and I'm in the one-half one-half and I just add them all together,

Ben: I once had a professor tell me that um, well if you got the right answer, you certainly know how to do the problem. I had to convince him no sir, you can jiggle these numbers any way you want. And come up with the right answer if you know the right answer in advance. Of course we're not sure that this is the right answer.

Anselm: It's been pretty good. Except for h-bar [seize two]. All right so somehow we need to get eight-ninths and one-ninth?

Ben: Yeah. Somehow.

Anselm: [muttering - reading?] If we were somehow free to swap around some of these square root of two over threes, then we could make it.

Ben: No they came from the table.

Anselm: Yeah, but I'm saying if we were.

Ben: [shakes head]

Anselm: I know we're not.

Ben: Wishful thinking won't help.

Anselm: We would have to—yeah somehow it would only be the square root of two-thirds would have to multiply both of these.

Ben: We can always [unclear] from class. You made me late for class this morning.

Anselm: I! You were the one, excuse me,

Ben: You insisted on going over problem 37 and

Anselm: My last semester of college I've never been late to class before and it's all your fault. Ruined my record, man.

Appendix F

Transcript 6

The transcript below is from a discussion that faculty members at the Governor's School of North Carolina had in the lounge of the faculty dorm. One faculty member, Steve, asked what I was teaching in my class and mentioned that students wondered if humans would "blow up" in space or not. The faculty began discussing this question and began to tease apart different factors by considering what would happen to a statue in space (this statue was Michelangelo's *David* and references to David in the text are regarding that discussion). This discussion then turned to whether or not a human would freeze while in space or heat up from the sun. This lasted much of the afternoon and we agreed to continue on the following Sunday. They began the discussion the next Sunday by wondering how the Earth heats up and cools off, which turned to a question about seasons: are they due to the elliptical orbit or due to the tilt of the Earth? The transcript below starts with that question. ("Leslie" in this transcript is me—the author.) Leslie:

Okay, so where are we now on the ellipse question?

Tom: I think this whole, if the sun is not at the center of the ellipse but is one of the foci of the ellipse [which is true] I think this whole business thing

?: Is all about the atmosphere filtering

Marc: Un-unless you—unless we could measure and discover that, one hemisphere's average temperature is different than the others

Joel: Well but the earth is much fatter in the middle, you know what I mean? So the part that's that's facing the sun, the closest part to the sun the on that's getting the most direct rays is always the equator. Because that's the way it works. And that's the nature of the angle of of the—

Marc: That that’s shape?

Katie: Mmm hmm has to be, that’s what makes the equator

Cameron: The equator’s not always the closest part to the sun

Marc: Right but it’s always getting the most direct sun.

Cameron: Not always.

Marc: No no it’s true.

Cameron: That’s what the tropics are about.

Tom: Yeah that would only be true if—

Steve: That’s that’s – it’s some sort of area—

Marc: Right right I see.

Katie: You’re right, but still that area—the belt. The fat-belt.

Leslie: So why does the tilt matter?

Steve: Well they think it’s ‘cause the (laughter) – well here’s the thing, now I have a problem for all you people you and your filter (laughter) is that that’s fine I’ll accept your filter all if you can explain to me why even when the earth is demonstrably further from the sun we don’t have any differences in temperature between north and south pole?

Tom: Why does angle matter more than distance?

Vic: Or why is distance irrelevant?

Steve: Or- right, why – how can distance be irrelevant if the earth is much further from the sun at some points in its orbit and the average like if pick some spot latitude and long and like halve the southern and northern counterparts for it--?

Vic: But wait wait wait--

Steve: But if it’s going that much further farther away why is the temperature not that much different?

Vic: But wait wait-- I have a thought right – this is not a question of like, that we can, like if there was a fire in that fireplace and the farther back I move from the fireplace the drop in temperature— there’s atmosphere involved. The heat’s traveling in a different way. So that it’s not a question of, like, radiant heat. The heat that we’re getting from the sun is a question of light, right?

Katie: Yeah because that once we get into space it’s cold out there.

Vic: Right. Heat’s not traveling through space in the way that radiant heat does.

Marc: How does heat traveling through space?

Katie: As light.

Vic: As light. As energy. And and then the atmosphere bends the light.

Katie: Once it hits something [Tom: that makes sense to me] that gets [Marc: heated up]. It's like And then it can't get back out.

Amelia: Right. It's trapped.

Vic: Because of the atmosphere.

Katie: Once it turns from- -I don't really understand this but it seems like it turns from light to heat but it's all energy but it's

Vic: We're into the angle theory.

Marc: It turns from energy to heat. Not necessarily to light to heat because there are other forms of non-visible light.

Amelia: Okay. So therefore when the

Katie: Energy in the form of light

Marc: Right gamma and — —which is nonvisible light. Infrared.

Amelia: Which would might wonder why there wasn't necessarily why there wouldn't be a huge different in temperatures in the northern and southern hemispheres.

Cameron: So are you saying?

?: Yeah?

Cameron: So are you saying that the angle doesn't matter?

Steve: No, I'm just saying that if – if we don't think distance does matter then we have to be able to explain why distance doesn't matter. And why--

Amelia: He's tough—he doesn't let you get away with anything.

Steve: —even though the earth is much further from the sun at some points in its orbit summer temp maybe is—

Marc: But we don't know about that – it's possible that there is a different average temperature.

Steve: Well but you were just saying that you didn't think there was.

Marc: Well I asked and someone said: did you read the Antarctica book? And she said—"I don't deny that it can get pretty damn cold down there—it's just the question is what's the difference."

Vic: Well it- the other question is then why is then the different planets does it seem to get colder the farther away from the sun? Right—like Pluto is like frozen solid.

Steve: Is that just because they have different atmospheres?

Vic: That's exactly what I'm wondering is that is it a question of distance?

Marc: Well clearly it has something to do with distance because we don't feel the heat from other stars—I mean distance has something to do with it.

Tom: What’s the temperature on Jupiter- I mean it seems the gas—

Vic: What’s the temp on Jupiter [singing]

Steve: What’s the moon’s temper—what’s the moon’s atmosphere like.

Marc: There is no atmosphere.

Vic: Right.

Steve: that’s not true—there’s atmosphere on the moon.

Marc: There’s no atmosphere there.

Vic: A really reall— it doesn’t enough gravitational force all on its own to have significant atmosphere. It has very very thin atmosphere.

Cameron: So what’s the difference between temperature on the moon between day and night?

Marc: Oh it’s huge! It’s enormously huge. [Why?] There’s no atmosphere to trap in the energy—it’s like the greenhouse effect.

Tom: You can’t have temperature without an atmosphere?

Steve: But I thought we couldn’t have heat without [couldn’t have what?] heat without atmosphere.

Marc: No, see—I’m not sure I ever signed up for that.

Marc: No there is such a thing as radiant heat—that’s what the sun—

Steve: But if it’s in a vacuum, I learned last week that space is a vacuum.

Vic: That’s what I hear.

Katie: I learned that science doesn’t suck.

Cameron: But if you put something on there, like a thermometer, which is measuring the temperature, it’s hotter in the day because it’s absorbing the

Vic: light and rays and things. Right ‘cause it—then there’s no atmosphere at all to filter it and it’s just absorbing everything.

Marc: Vacuum means, by the way there’s no— I don’t know first of all , I was going to say something that there’s no mass but these electromagnetic waves they don’t have any mass really so you can still call something a vacuum. I don’t know we’re getting technical—there’s a lot of energy in space! It’s filled with energy.

Steve: Right—right, but that doesn’t make it heat.

Tom: Yeah weren’t we talking about if you’re just completely in outer space, not exploding (laughter) it’s we decided it was meaningless to talk about heat isn’t that right? And so presumably isn’t that the same thing if you’ve got a planet without an atmosphere? Then it’s just an object in space? That's just like you standing there in your space suit trying to measure the temperature.

Marc: but it's HOT on the sunny side of the moon—it's hot.

Tom: It is?

Marc: yeah.

Steve: So the moon has enough atmosphere to create heat.

Cameron: So I think what we've learned here is that, [Katie (to Marc?): How do you know it's hot?] uh, is that the atmosphere helps, like, mitigate temperature change.

?: The surface itself? We can do that also with looking at other planets, right.

Tom: Well but then it's reflected too, right?

Marc: Say again (to Katie?)?

Katie: Like if we know what the atmosphere is like on other planets and they have--

Marc: Like Venus for example, Venus is very hot

Amelia: We are mostly water and it does reflect light which bounces back and forth.

Marc: Yeah yeah—the atmosphere reflects most of the light—

Katie: Yeah if it were too hot up in here we would be just

Marc: We would fry.

Amelia: Well the oceans would evaporate.

Katie: yeah that's I'm trying to say.

Marc: The oceans would boil the four horsemen—

Steve: By the way when we're done with this I have to tell a story about what the priest said at mass today—it was nothing about prostitutes or anything like it was last year.

Amelia: Did he talk about the four horsemen apocalypse?

Steve: we talked a little bit about the apocalypse— it was actually pretty good. [Conversation turns to discussion of weekly happenings.]

Vic: [Yelling to get attention] Heat of the sun and the moon and the stars!

Steve: Alright. Heat of the sun and the moon and the stars.

Leslie: Okay—put a thermometer. It's gonna do?

Katie: I'm pretty sure that the mercury's gonna leak out.

Amelia: And then it'll float in these little silver balls.

Tom: How does a thermometer work again?

Katie: That's pressure – a thermometer has to do with pressure so it wouldn't do anything in a vacuum.

Marc: No a thermometer isn't pressure- barometer is pressure.

Steve: How do you get the mercury to move?

Marc: Okay- what happens is, your particles have to interact 'cause I remember as a kid reading somewhere that if you could actually get to the center of the sun it's so gaseous the particles are so disparate that you actually freeze to death because there wouldn't be much interaction between you and the particles of the sun.

Steve: You'd need a hell of a space suit to get there though.

Marc: That's what I'm talking about. And you be blind by all that light. But actually there's no particle interaction so I'm assuming that- I'm imagining that if you take a thermometer and put it into the vacuum of space there are very few molecules to interact with your thermometer and that's why it's cold out there. So the question is—and I remember this, this is a question in science—how does energy travel? That's – they tried to prove there was an ether in space! [right] And they found out there's no ether, so how does energy travel in space? [right] It's electromagnetic waves.

Amelia: What do what do we call this stuff?

Katie: I wish you were a little smarter.

Steve: I do too.

Amelia: Most of space is that stuff and there's that other stuff.

Steve: But- alright so like thermometers in space—

Leslie: No no—just a thermometer on earth, how would that work?

Steve: Okay—

Tom: What is it about mercury, what happens to it?

Marc: well it expands. But it—has to be hitting the bulb, I mean like the heat that the gas- the air. [it's what heat it] yeah—what?

Tom: Heat is like the —

Marc: Heat is a measure of the amount energy—the motion of molecules.

Tom: There has there has there have to be molecules moving to measure heat. That's right.

Steve: But how do they—wait a minute—look.

Katie: So you go into space where there's a vacuum and there's no molecules out there to interact with the little bulb at the bottom the mercury inside, it's not gonna measure anything.

Marc: That's right. And that's why it's cold in space. Because your body doesn't feel any of those molecules either.

Steve: Wait a minute. Because sometimes you have [Katie: I'm afraid we're guilty of reification but ok] but sometimes you have thermometers that are in the sun and in the shade right next to each other and the sun one is much hotter.

Marc: That’s because the air surrounding the hotter is moving faster and in the shade.

Amelia: And if the vacuum has no air.

Marc: You’re right, then you wouldn’t measure anything. We’re agreeing.

Steve: Does it seem like Weitz agrees with everyone?

Katie: Nuh uh he’s been fighting with you all afternoon.

Cameron: Even when you agree.

Amelia: Yeah- he even says for you to shut up (?)

Leslie: Okay guys I’ve got a thermometer in space, one is in a box and one is facing the sun so one can’t see the sun and one can. Are they gonna measure the same non-temperature?

Cameron: What’s in the box?

Leslie: The shade.

Marc: Well is it the vacuum of space?

Steve: Lava.

Leslie: Still in the vacuum of space.

Katie: Wrapped in leather.

Marc: No no wait a second but you’re right though because um for example, solar panels that face the sun—like if you had a satellite with a solar panel and it’s facing the sun the carbon fibers, everything’s expanding. That’s how they sometimes lose these satellites because—so the energy

Amelia: Marc talks too much.

Katie: is he like this in every class?

[Laughter, jokes about Mr. wizard and kids.]

Marc: So it must be - it must be- a temperature. Well, there’s heat in space. I mean your satellite.

Vic: The object is absorbing the energy by the light.

Marc: So would the thermometer absorb the energy?

Vic: Why not?

Marc: Well then- then we have to change our answer then the thermometer would rec—?

Vic: I was going to say that all along—I don’t know what you guys think (?)

Katie: I’m not saying that— it seems like the way the thermometer works though it seems like it wouldn’t register. It might

Tom: I don’t quite understand how a thermometer works

Katie: Well—

Tom: ’Cause we’re talking about heat.

Katie: Weitz?

Marc: What if the what if the what if the energy that's – the gamma ray and the infrared and whatever—what if all of that electromagnetic energy excited the mercury in the ball and it expanded? Then it might measure something.

Katie: IF that's how a thermometer works then, ok.

Steve: How do we—is that how a thermometer works?

Vic: Is there a reason that a thermometer can't absorb energy?

Marc: Is there a reason why? That was your question? [right] is there a reason why it might not absorb—

Vic: And then there's the question of whether or not.

Steve: What's the intake on a thermometer?

Marc: It's a metal bulb – it's just

Steve: It's a metal bulb that's exposed. And like the thermometer could be put in our mouth.

Katie: A thermometer that you put in your mouth—it reacts differently than a thermometer that you have outside because if I if I am right the thermometer I have when I'm sick it does not measure how cold my house is. Am I makin any sense?

Vic: I dunno.

Katie: When you when you don't have it in your mouth and it's not actually touching anything

Marc: Right then it yeah

Katie: It might be warm or cold but it doesn't say my house is – [yeah]

Amelia: How many ways are there to measure heat?

Marc: But but mercury thermometer does—sure it does. You shake it out and—

Leslie: Amelia just asked—

Marc: Oh. What was your question?

Amelia: How many ways are there to measure heat?

Cameron: That's only one kind of thermometer, right?

Katie: That's what I mean that's what I'm tryin to say. The difference-

Cameron: You're saying something different.

Amelia: 'Cause that's not what they use in space to measure temperatures like on the moon. What—why are we even talking about this?

Vic: Are we completely distracted?

Katie: She asked us what a thermometer would do in space.

Amelia: But she didn't say what kind of thermometer.

Marc: But in order to measure heat you have to have something reacting with the environment. [ok] so if it's not mercury it's— silicon in a chip or something- something has to be reacting with the environment and my question is [well my] is there anything in space to react with.

Amelia: But temperature is measured on the moon is it not?

Marc: That’s what I’m- I agree with you.

Amelia: So how do they do it? She’s not going to tell us, I’m sure. How- how is temperature measured on the moon? If it’s been done then how—

Marc: But the question is why is it so- why is it so cold— It’s measured some way! It’s measured some way—let’s, I can agree it’s measured some way but take that measuring system and put it in space. Is there anything that it can react with? Is there any particles in space—wait, what’s our question again?

Leslie: We put the mercury thing up there—a normal thing up there—it’s gonna have a reading on it. Is that reading going to tell you the temperature or is it just—it doesn’t work any more?

Marc: Well it it should, I mean—it’ll be very very cold but there’ll be some heat there.

Steve: Mmmm. I disagree.

Katie: The question, I think, is will the thermometer measure that heat—does it work in space?

Marc: There—there aren’t many particles for it to interact with which is why it’s so cold I guess.

Steve: It’s a vacuum though.

Marc: There aren’t any particles though.

Steve: But the moon has— if it’s in space—

Marc: The moon is a rock—it interacts with the gamma rays [in background Amelia, dark matter?]

Steve: Neil Armstrong bounces. On the moon.

Vic: That’s correct—but yeah that’s gravity and not necessarily the atmosphere.

[Amelia, in background: ‘only this much about dark matter—and if they don’t know and by they I mean the scientists, how are we supposed to know.]

Steve: If we didn’t have gravity we’d ____ on the moon.

Marc: That’s correct—so you might, one could argue that the moon has one sixth the atmosphere since it has one sixth the gravity.

Leslie: That was Amelia’s— I didn’t hear your last comment.

Amelia: Oh I was talking about—I mean, isn’t most of space dark matter and then some of space is dark energy, right? Or something like that?

Leslie: We don’t know.

Amelia: We don’t know—like we don’t even know what dark energy is and barely know what dark matter is, and so if scientists who study it don’t know then how are we supposed to know what’s happening.

Leslie: Well the thing is either our theories are wrong or there’s mass we can’t find, you take your pick.

Amelia: But what I’m saying is, nobody knows

Leslie: Right. Yeah.

Marc: I still think it has to do with the amount of particles to interact with—in space there are few particles so there’s very little heat cause you’re not feeling it it’s not—well not very little, yeah— but on the moon it’s a big rock so it’s taking all of this energy and it’s interacting with all of this energy that’s coming at it.

?: Something about atmosphere

Leslie: Well what’s so special about the atmosphere that helps it?

Tom: Well there- there wouldn’t be a temperature around the moon but the moon itself—

Marc: The moon itself has a temperature.

Vic: Wait wait wait—no no—this is

Katie: You could plunge a thermometer into the moon. Like a turkey [laughter] into one of the crevasses of the moon.

Marc: Up the moon’s butt. And baste the moon a little bit. [break]

Vic: The problem is the problem is—the lack of significant atmosphere on the moon means that one side is going to be very hot and the other side is going to be very cold.

Tom: Because the atmosphere tends to preserve the temperature.

Vic: Right. The atmosphere is going to stabilize it the earth is within a certain temperature. And then there are other weather patterns that happen in the atmosphere that might move that energy around.

Marc: It also serves to reflect.

Steve: I think an atmosphere matters because radiant light hits the one sixth, whatever, atmosphere of the moon there are particles to hit— that that light can, I don’t know, whatever, I’m making it up not— triggers molecules to move, creates heat.

Marc: but that’s not the only source of heat that heats the moon. The moon itself absorbs a lot of the radiation that the sun is giving off.

Steve: Right but that’s the way it—

Marc: the ground absorbs radiation.

?: Why does it need to be atmosphere?

Steve: Well I guess- the reason I’m thinking atmosphere matters is because if we don’t have atmosphere—if you don’t have like – spaces of vacuum [the rock] right right or where you have. So a rock-lava-David— David— is in space— does he get hot?

Marc: Yeah.

Tom: David can have a temperature because because he is made up of molecules which are

Steve: So if David passes in back of, like, Venus de Milo, and is in the shadow for like a little bit and then moves back into the sun, David warms up?

Marc, Tom: Yeah. Pretty much.

Tom: That makes sense to me.

Marc: That makes perfect sense.

Leslie: Does he keep warming up indefinitely?

Steve: Right.

Marc: No because there’s finite amount of—he would reach a stable point.

Leslie: Why?

Vic: Yeah- why?

Vic: There’s no way for you to give off that heat—there’s no way for you to radiate that heat.

Marc: No but you do- but you do radiate the heat.

Tom: you don’t heat up indefinitely

[Many voices.]

Marc: Because all matter would evaporate.

Steve: David explodes eventually.

Marc: Ok, yeah- eventually the earth explodes—but that’s not what we’re talking about.

Vic: The earth explodes?!

Steve: Yeah- that’s what the priest was talking about.

Marc: That’s only if we sleep with prostitutes.

Katie: The priest said the Earth was gonna explode?

Steve: You shouldn’t believe Pentecostals.

[Discussion of a recent field trip to a church.]

Leslie: Well is this what’s causing global warming—just that the sun keeps shining on the earth?

Marc: No it’s the thickening of the atmosphere that’s trapping more and more.

Cameron: But the energy can’t get out.

Vic: Yeah why would why would- that’s would, I guess that’s true, so why would the energy have to be spent as heat? Like radiated as heat from the David floating in space? Or could he not give off his heat—

Cameron: So why can’t we radiate heat out—

Marc: Well we do radiate heat out but the increasing density of carbon dioxide is trapping —

Vic: We're not worried about the Earth we're worried about David.

Cameron: I'm talking about a guy floating in space.

Tom: Oh so global warming—just forget about that.

Steve: For the time being.

Marc: David does radiate heat. David does radiate heat.

Amelia: But only for a while, right? Is he radiating it as fast as he [?] it?

Marc: Once he reaches a stable point—

Katie: you can't play that card [?]

Marc: why?

Marc: Okay– let's— let's say David is in a shadow, right? Okay- he enters the sun. The sun bombards him with all this energy right? So in a second it's now at 5 degrees. Can it radiate heat that fast? No. So in the next second it's 10 degrees. It's now radiating a little bit more heat but there's more energy coming in. So it gets to 15 degrees. But at some point it's radiating enough heat to stabilize at 20 degrees.

Steve: But why?

Cameron: What?

Marc: Or let's think of think of like a, think of like a basin, ok? Think of a tub. With the drain open, okay? The drain is open. Now if I open the spigot [Uh huh.] – if I open it too slow then the tub doesn't fill. But if I open the spigot fast enough there's water filling up the bottom, and yet some is also draining out, right? [Right.] If I open the spigot up fast enough it doesn't matter if the bottom is open, the top will overflow but at some point if I reach the right point the tub could stay at a certain level, even if water's going in and water's going out, right? If they came in at the same rate [Steve: Right, but—] the tub would fill up.

Steve: But that's – what's David's drain?

Vic: That's—this is my question. What's David's drain?

Tom: Well, what's the sun's drain? The sun is clearly radiating heat and energy.

Marc: Yeah I mean that's just the—

Steve: The sun is radiating *light*.

Vic: I want to—

[Many voices.]

Marc: And gamma rays (in response to Steve) and x-rays and all these other things.

[Amelia squeals to imitate being bombarded with rays.]

Steve: The sun is giving off light rays.

Marc: It's giving off a whole—

Cameron: Why is the sun so special that something else can't give off energy in whatever form?

Steve: Well the sun's giving off light—

Vic: so it's generating

Marc: and radiation and stuff.

Cameron: So it's all about the light.

Steve: yeah right I think it's about light.

Cameron: that's the only kind of energy.

Vic: no no there's radiations and stuff.

Marc: let's say the spectrum the electromagnetic spectrum.

Leslie: If you say light you don't necessarily have to mean light—

Steve: I just mean like, rays.

Vic: Radiations.

Steve: So I thought that we were saying that – or y'all were saying that the Earth is warm North v. South we have seasons because of the way that light interacts with the atmosphere, right? And filters it at different angles.

Marc: The atmosphere will reflect—*reflect* not absorb—will reflect more sunlight depending on the angle at which it's tilted towards the sun.

Steve: If the earth didn't have an atmosphere.

Marc: Far less light- far less energy- would be reflected and the earth would be a lot hotter.

Vic: Oh oh oh oh oh oh oh oh . Oh oh oh .

Marc: The Oceans would boil the apocalypse.

Tom: If the earth did not have an atmosphere there would be no seasons, right? Because.

Marc: No no—yeah yeah yeah.

Vic: I had just had an I had an idea well- or at least about why distance is at least partly significant in terms of the amount of heat that an object absorbs, right?—that – that if you've got a source of of the radiation stuff, then it all goes back to surface area again. So that if you're Pluto and your're this far away, the amount of surface area that you have exposed in terms of this circle that's radiating heat—the closer that you get the more of your surface area is going to get sort of—

Marc: This has to do with size—Pluto's much smaller than the Earth.

Leslie: Vic, do you think Marc understood you?

Marc: I'm sorry.

Vic: I—I don’t think he did.

Leslie: Marc do you think you understood Vic?

Marc: I thought I did, but given his pause I don’t think that I did.

Vic: Alright—if we can go back to the moon, right? [ok] If if the moon gets in the way of the sun and it blocks out the entire sun it can only do that because of the distance because of the relative distance between the Earth and stuff.

Marc: And the relative size.

Vic: Right. So that- if the moon were closer [to what?] to the sun they would block out less of the sun— or or more! [laughter.] Or more! Or less!

Leslie: No wait—more or less—which one? Both?

Steve: It would block out less of the sun.

Marc: Think about putting your hand on a screen—making a shadow puppet. The closer you get to the light source—

Amelia: The smaller it gets.

Marc: The bigger the puppet.

Amelia: No.

Tom: The closer you get to the source of the light?

Marc: My god we’re getting— I don’t know now.

Vic: Right right—

Amelia: Oh the source! I’m sorry I’m sorry.

Vic: Closer to the light you’re absorbing more of the light.

Marc: That’s right.

Vic: Your hand hasn’t changed size—now the closer it gets to the screen the more it absorbs. That’s exactly what I’m saying – so the clue (?) this hand puppet far away absorbing a little bit and that – Mars is the one that’s closest to the sun so it’s absorbing more of the thing

Marc: Over those huge distances it makes a difference.

Vic: Regardless of how—yeah—regardless of how much surface area.

Marc: That’s right, but then over such large distances distance makes a difference but given just the tilt of the earth I’m thinking that the tilt has much more to do with it.

Vic: No I’m just talking about why- why distance is still significant.

Marc: Well of course distance is absolutely significant.

Cameron: Distance is not significant it’s the amount of diffusion that happens within that distance.

Vic: Okay.

Leslie: What do you mean ‘amount of diffusion’?

Cameron: Like—when my hand is closer to the projector—with the projector the lens makes the light go like this—so it’s more diffuse when you get out towards the edges and the band, width is narrower when you’re closer to it. [Marc: radiates]

Leslie: So it gets weaker as you go out.

Cameron: It’s the same amount of energy but it’s spread over—

Leslie: Is it solely because of what Vic said—is it just because it’s going over more area or is it also just losing energy as it travels?

Cameron: It’s probably losing energy as it travels, too.

Vic: Wait though it—

Cameron: Well, it’s gonna hit other things.

?: You’ve got (?) atmosphere.

Vic: Yeah ok sure.

Vic: I’m thinking in terms of stars and stuff—

Marc: Light weakens the further away you are, that’s why we have brighter stars— well one of the reasons why we have brighter stars and dimmer stars is that the energy that the light has decreases.

Leslie: But is that because it’s just traveling further or is that because – well, how should it decay if it’s just because of distance?

Tom: Inverse square, right? Because it’s—uh—

Marc: Because you have three dimensions.

[Laughter.]

Leslie: [To the tape recorder.] Okay—Tom is taking his hands and flinging them apart over and over again.

Tom: Don’t you see? Can’t you see?

Marc: I gotta listen to these tapes.

Marc: what question are we pondering?

Leslie: I – I happen to know how fast light decays—and if you could tell me what it would be if it were only due to area—that it takes up—that the area that the light’s going into is getting bigger—

Tom: Right right right! That’s it the area is getting bigger, so like—damn.

Marc: So it would have to illuminate an ever greater source of area so each individual point gets less.

Cameron: That’s what I was talking about earlier.

Leslie: That is—so I’m wondering why Tom thought it would be distance squared. So if I’m close to the sun it’ll be x bright , if I’m twice as far away it will be one fourth.

Marc: [Sighs.]

Vic: So that- you win. It is distance.

Marc: Look the distance between earth and Pluto has to do with distance but the difference between winter and summer has to do with tilt, not distance.
Steve: But tilt is insufficient by itself. Tilt —
Marc: I mean ap—I mean angle of incident energy. That is correct.
Marc: So then I can guess maybe distance has a component.
Steve: I'm troubled by David. I want to know why he radiates heat.
Vic: You mean how he gives off heat?
Steve: I want to know why he gets warm and why he can radiate.
Marc: He reflects—I'm not sure that he radiates. Well—
Tom: He will reflect.
Marc: He'll reflect him because we'll be able to see him.
Steve: But where will it go?
Marc: That's how we see it. We see it because he reflects.
Steve: But it's not light it's heat.. it's not *heat* it's light
Leslie: Does it get hotter at all? Does he absorb any of it?
Marc: He absorbs it—that's what gives him a temperature that we can measure.
Leslie: Ok—why does he stop? Or is he always going to keep on absorbing it.
Steve: Right. Because there's no way—there's nowhere for that—
Marc: His temperature will change depending on his relation to the energy source. If he's moving towards the sun he's getting hotter if he's—
Vic: Right but to borrow your bathtub metaphor right if he keeps—if he keeps absorbing energy without being able to—
Steve: He's going to overflow.
Vic: He's going to overflow and blowup.
Marc: But he is—he is – I could imagine—I could imagine perhaps-- tiny thing, MAYBE, blowing up. But a certain size would be able to reflect that at a good enough rate that it would be able to stabilize.
Steve: But if he gets hot—I'll buy that he reflects—but if he also gets hot—either there's some way that he gives off heat or
Cameron: I say that he's radiating heat.
Steve: But how can he radiate heat?
Cameron: How can he not radiate heat?
Steve: There's no where for the molecules to go (?)

Marc: Ok but this is very tricky. Electromagnetic radiation travels in a vacuum. How does that happen? I don't know. But it happens. Now if we want to sit here and think—I mean that's

Steve: That's what happens the light hits David—on David—it, the light becomes heat and then it eventually becomes something other than heat and leaves David?

Marc: Ah- no energy hits him. It's absorbed. It's also reflected. And as it's reflected it takes some of it's energy with it in the form of a different type of energy because —

Vic: Right right right ok—again what we keep getting at or I think that what my trouble is with Steve here is again

Steve: Not with Steve, with my concept

Vic: I'm sorry—your concept. I am in agreement with your concept.

Steve: I mean I understand having problems but like let's maintain boundaries (laughter).

Marc: So what happens is—this is the sun coming in and it's very wavy – it looks like a nice ruffles potato chip, right—it comes and it hits the David and some of it is absorbed so its molecule are beating right and some of it is reflected in the form of something less wavy.

Cameron: The problem is, I think, the distinction between energy and heat.

Steve: No, that's not the problem.

Tom: But I still don't understand (Steve: Tom is with me) so that the energy from the sun is always striking David and some of that is being reflected.

Marc: That is correct.

Steve: So David is accumulating energy.

Marc: At a certain rate-- in one second it gets a certain amount of energy in the second second it gets the same amount of energy

[Many voices.]

Steve: So if it's always in the sun it's going to continue to collect infinite amounts of energy?

Tom: It would end up start reflecting as much energy as—

Marc: Think of it- think of it like a rhythm, ok? Boom boom boom boom right so- it gets energy and it reflects and it gets energy and it reflects—so it's constant—it's just its just it's just stable.

Steve: It's not stable! [many voices]

Marc: Then it would not it would not it would not! you're thinking of something that—heat is measured by ticking, right? Tick tick tick ok? what you're saying is the sun is hitting it and it’s constantly accelerating because it’s constantly getting new energy, right? Tick-tic-tick-tktktktktk! Pow! Right- that’s not what’s happening—it’s just tick, and some energy comes in just as it’s about to slow down it gets new energy so it—it’s that energy that keeps it at that constant rate.

Steve: I don’t buy equilibrium.

Marc: Uh uh?

Steve: I reject that. I reject the assumption of equilibrium.

Vic: Because then David would never ever change temperature.

Marc: It would if it got closer or farther away- lets say that it’s traveling.

Leslie: Let’s keep David still! Let’s keep David still for now.

Marc: David is still- David is not moving. Energy comes in—it vibrates, right?

Leslie: So did David heat up or ?

Marc: It did just heat up, ok? — now what keeps it going? It’s the next calorie calorie of energy that keeps it going—without that calorie of energy it cools down. Some of it some of it set the molecule in motion and some of it reflected away. And then the next calorie comes—

Steve: Wait wait—right before that last- the second burst of energy it was at zero again?

Marc: Well maybe.

Steve: David’s back to zero.—what you’re saying is energy hits—one—half leaves half [half stays] stays—[that’s right] and then sort of withers. [then meanwhile the next one comes in]. I reject that too but I understand your logic.

Marc: At least I’ve been heard.

Leslie: In your system is energy conserved?

Marc: Yes—because some of the energy has been absorbed and some has been reflected and that hopefully should equal the same amount of energy coming in.

Leslie: Ok—the energy that’s absorbed is it lost forever or does it somehow escape back into the universe?

Marc: Ah—is it absorbed forever? Well it’s stored in the temperature of this thing! If I could take that and heat water with it, I’d have recovered the energy.

Vic: Huh?

Marc: That’s how we—this thing has energy- it’s like it’s like it’s like a computer – it’s memory. It’s storage.

Steve: Does that mean it will heat up?

Marc: No – because it’s not, it’s not, the rate of the vibration of the molecule is not increasing infinitely it’s just getting energy. Without that energy

Steve: Molecules get energy and stop, molecules get energy and stop.

Tom: And why do they stop?

Marc: Well they reach a stable—you’re assuming that it’s preordained that this one , I mean, if the energy’s coming in too quickly it will, I mean—it’s not preordained that it’s going to tick like this I mean maybe it will tick like this—maybe it’s really oneoneoneone— but eventually it’s going to be reflecting it at a stable rate.

Cameron: I don’t think reflecting is the right word.

Marc: or radiating.

Cameron: It’s getting rid of energy somehow and part of your problem is that you’re assuming is that it’s a linear- it keeps getting more heat and it keeps reflect—or getting rid of , or excuse me energy, keeps absorbing more energy and keeps reflecting energy at the same rate.

Steve: I don’t understand what—

[Many voices]

[Marc simulates being pushed like a pendulum.]

Marc: Just give me a push that way ok? Good. Now I jumped all the way here.

Leslie: Now wait—if you start with some energy, why did you slow down and stop over there?

Marc: Well, ‘cause I don’t know—molecular forces— because that’s the only amount of energy he gave me! So come at me again—

Tom: Wait no no no—you slowed down and stopped because you were running into something.

Marc: I was running into something the the the—David has intermolecular forces, ok? So it has—the weak force the strong force it has these intermolecular forces, it pulls it back right? So push me again.

Tom: SURE! [Laughter.]

Marc: And I don’t mind—right and if he punches me *harder* I go *farther* but if he’s punching me at a constant rate I will only go the same distance every time, I won’t eventually go out the door unless he starts punching me harder—but I’m not *accumulating* energy here I’m going to the same spot every time.

Leslie: So you’re not accumulating energy.

Marc: That’s right—I’m not accumulating energy.

Leslie: Then where is the energy going?

Marc: What do you mean? He’s just sending it out and I’m absorbing it and I’m going back and he’s sending out the same amount

Steve: But if you absorb it that means that you keep it [Marc: keep it]

Marc: Well the energy’s going into my running back and forth ok? this is where the energy’s going it’s kinetic energy! I’m now running back and forth, right? But I’m going to get tired unless he pushes me again I’m not going to have the energy anymore—

Steve: But the energy doesn’t—I’m no physicist—but I don’t think energy just disappears like that.

Marc: Where is it disappearing? it’s stored in kinetic energy—if I’m on a treadmill I can turn a turbine. If you put me on a treadmill you’re using my running energy.

[Voices.]

Marc: Wait wait wait- stop a second! This is where the energy is- it’s kinetic energy this is usable energy!

Amelia: But Marc if you’re still the energy—it’s still in you.

Marc: I don’t know where that—in the example he’s pushing me right? And you want to

Leslie: Let’s think of when you turn around—are you moving?

Marc: That’s potential energy—right? I’m about to go BACK—if you could stop me here you could put a treadmill—I have the ability to work the treadmill.

Vic: I’m having serious problems – reconciling the metaphor has taken on levels of complexity.

Marc: When you stretch a rubber band is there energy in that rubber band? Yes—it’s the amount of energy

[Jokes and laughter.]

Steve: Marc I think you might sit down. [To Leslie] Can you give us a little bit of guidance.

Leslie: Um—I I sense that the rest of the group disagrees with him (Marc).

Amelia: I don’t.

Cameron: I agreed with Marc too until he started talking about potential and kinetic energy and then I wasn’t buying that.

Vic: I was on the fence.

Steve: I was so not on the fence.

Leslie: Can you illustrate in a way that makes sense to Marc—and Marc you’re going to have to listen—[I’m listenin!] and I want you to be able to repeat Steve’s argument back to him, not in Steve’s words, in your own words. [Ok]

Steve: So—David's in space David is hit by energy [x] x amount of energy. Some of that energy is reflected off for some other—in the form of light back somewhere else. The rest of it hits David and is absorbed by David and David's molecules start to move more quickly.

Tom: So at some point- perhaps when David's molecules start moving quickly enough, he actually starts to radiate energy in a different way.

Steve: But then the question becomes: if he's, so if only a part of that energy is what's reflected off in the form of light (a few jokes) um.. but if the light continues to hit and only a part of it goes off then [explodes or melts] is heating up, right? And then my question is, and it's really just a question, because David's in space, so he's not surrounded by molecules that could be heated, so they'd be, so he'd be able to radiate, Marc, how does he, how does this rock have the capacity to radiate anything if there's nothing except for light, space and David—there's nothing for him to radiate for heat to be transferred out. So—I think, the way I see it is that the light comes in, part that's reflected off, the rest of it sticks in David, and because energy doesn't disappear David just continues to heat up and maybe explode. I don't know—

Cameron: What happens when he explodes?

Steve: I think when he explodes, then there are smaller chunks of David.

Leslie: The moon, so far, has not exploded.

Tom: I mean things don't explode so we're missing something.

Steve: Right, but there's somewhere—if David is really in space, and so he's surrounded by a vacuum and it's a perfect vacuum, then there's no other molecules surrounding him that can carry radiant heat.

Cameron: Ok- I have a question. Marc said that radiant heat is not the only way it can expel energy.

Steve: Right- exactly--- no and that's what I'm looking for, is I just need some help on where.

Marc: Let me ask you a question—how did that energy get to David—David's in a vacuum—how did that energy get to David in the first place?

Steve: I'm not fully convinced that David even heats up because he's hit. I'll buy that he's hit by energy and I'll buy that he sends some of it off [that's fine] but then does he not absorb any of it? And if he does then

Marc: He does—he absorbs it and he heats up—he goes from some temperature to a higher temperature.

Steve: What’s to stop him from heating?
Marc: He heats to the point that he heats.
Steve: That’s teleological.
Marc: No- but it happens… [tape flips.]

Tom: And the light—David’s not going to produce it in the same way.
Marc: No but he’s going to radiate it in the same way.
Marc: Yeah.
Tom: What’s the difference?
Steve: Why
Marc: One is generating—the other is, the other is— look. Let’s
Tom: Well what are we—one is generating?
Marc: Let’s talk radia— let’s talk energy. Let’s not talk heat or light. The sun is generating energy. How does that energy travel? IT travels in a vacuum. Why can’t the energy— David IS generating energy. He’s generating energy because his molecules – it’s a different form
Steve: Only if he’s absorbing the energy.
Marc: That’s right—he absorbs it
Steve: That’s an assumption we’re making.
Marc: Right, but I’m saying he absorbs it. We know the earth absorbs it, we know the moon absorbs it. We know that molecules in a vacuum absorb energy that’s being thrown at them. That’s how the atmosphere heats up that’s how the earth heats up—
Steve: So only if—?
Leslie: So let’s say David’s green. [Ok ok David’s green.] What does that mean. Let’s assume it.
Steve: So he’s absorbs he’s absorbing green
Marc: He’s reflecting green
Steve: Oh reflecting green and absorbing everything else.
Leslie: Everything else- ok. so now this this is just easier to talk about—there’s the green light that’s reflected we don’t have to worry about that anymore. What happens to all the other light that he’s absorbing?
Marc: It’s absorbed by David.
Leslie: And then what? He just keeps heating up each time more comes in?
Vic: Ok here’s the thing—
Marc: You chose a stable color—green is a manifestation of stable energy. He is green degrees warm. Right?
Vic: Huh?
Marc: He will only be green degrees warm.

Leslie: [Points to a green shoe.] Is his shoe green degrees warm? The sole of Cameron's shoe?

Marc: It's a metaphor—it's a metaphor—they're always green.

Tom: It's the same temperature as the rug (in the room).

Marc: Well you know what it's probably not the same temperature have you ever had a black surface and a white surface? The black surface is hotter than the white.

Steve: Only—.

[Laughter.]

Amelia: Black cars are hotter than white cars—that's why people who live in deserts drive white cars.

Tom: We're talking about things in an atmosphere. We're also talking about black which absorbs other forms of energy.

Marc: Yeah- but the analogy, you can see the analogy—different colors.

Tom: I can't—black, black is like all of the colors, white is none of the colors.

Marc: Ok so green is some of the colors so I can imagine that green would be warmer than white.

[More about colors.]

Leslie: The question about green was to differentiate between reflected light, transmitted light, created light, the green that we see from David is reflected light – it never did—David never had to worry about it. He just threw it away as soon as it came. The rest of the light gets in somehow and is no longer visible [right]. Ok.

Vic: It can not be being reflected.

Leslie: Right—and if it's absorbed—for a car, does that make it hotter?

Tom, Vic: Sure, yeah.

Leslie: Ok—so it's going to make David hotter.

Marc: Yeah.

Leslie: Okay.

Tom: But it has to go somewhere because David does not

Katie: heat up indefinitely

Tom: does not heat up indefinitely unless you [?]

Marc: But it goes in the form of green light! That's where it goes!

Leslie: No—we've already taken care of the green light—it's not like he gets brighter as he heats up, it's still just plain old—

Tom: And the light is traveling—there are all these different frequencies of light coming at David.

Marc: That’s right.

Tom: So where.

Steve: So every light – he’s heating up with ROY BIV and giving away green, right? So he’s accumulating ROY and BIV.

Marc: Right. Ok

Steve: And he’s accumulating it and accumulating it and accumulating it

Tom: He has to get rid of it some way we just don’t know.

Vic: So at some point does David become—

Marc: No but he gives it away in other forms of energy—heat- well infrared— Infrared primarily.

Vic: Wait wait wait you cant you can’t you can’t change ROY to infra-ROY.

Marc: Of course—(pauses)

Vic: You can’t you can’t give you can’t change ROY into infra-ROY

Marc: Well why not?

Vic: How does he do it!?

Marc: Because it’s ju- because as the rock absorbs the energy the waves slow down – it’s my frequency— it’s *this* [does the motion, hitting thing]—the rock absorbs the ba-ba-ba-ba-ba and it absorbs some of it so now it’s just—it isn’t visible anymore our eyes just aren’t able—if you wear infrared goggles.

Vic: I’m sorry I think the problem is that—that in addition to ROY and BIV, we’re already assuming ultraviolet and infrared, and let’s say that he gives away all those things, too, in addition to green. So he’s gotten rid of all of the infra and all of the ultra and all of the gamma

Marc: And you’re asking me where does it go? It goes in the form of that—you can’t dismiss that!

Vic: I’m NOT dismissing that! At all – what I’m suggesting is that we still have ROY and BIV that we- that he’s not changing it into something else—

Marc: But he *is*—

[Voices.]

Leslie: Can you come up with another way of explaining – I—I see the discrepancy, and I don’t think you understand the discrepancy and I’m wondering if there’s a way you might explain the discrepancy better—I have analogy I can use —

Vic: Wait wait wait—every—everybody is payin' me money. Everybody is paying me money in different forms—in dollars, five dollar bills, twenty dollar bills. [ok] I'm savin' all of my 1 dollar bills that I give away—I do not spend any of my dollar bills on anything ever. Which means that I am gradually accumulating 1 dollar bills—even if I'm spending it in 5s and 10s and 20s. so what do I do when I end up with 1000 dollars in one dollar bills that I don't know what to do with?!

Marc: I'm gonna change that analogy—or I could keep it I could keep it! Ok? I'll keep it fine—you know what I'm gonna do with those one dollar bills? [tell me]
Well—those dollar bills become— you you spend 50 cents of it in terms of heat and you throw the other 50 cents of it away but we can't see those 50 cents because we're only attuned—

Tom: You're losing the analogy.

Leslie: The question is: how did that dollar turn into 50 cents. If the only thing you can throw away is coins, what happened to the dollar bills.

Vic: I didn't cut them into the shape of coins and pass them out—I still have I have 1 dollar bills that I cannot break, I cannot change at the bank because there's no freakin' bank.

Marc: But I'll tell you what happens. If you really were [? [mocking: I'll *tell you what happens?*] if you really really really were ?—if you (someone enters and we applaud) you'd be drownin' in one dollar bills.

Vic: This is our point!

Marc: But *my* point is that you can't stop converting those 1 dollar bills to 50 cents! By the virtue of your existence it means you must be (?)

Amelia: What happened to exploding in space?

Marc: What no no no—o

Vic: Our question fundamentally is—is—*how* in what way did I change my dollars to 50 cents.

Marc: I'll tell you –

Then I interject, Steve notes that it isn't fun to "make stuff up" anymore and it feels like an argument and not a discussion. We take a break and don't resume.

Appendix G

Transcript 7

The fifth grade classroom in this transcript has been working with solar ovens over a series of weeks. In this transcript, they are discussing the relationship between light and heat.

Student: That you can only heat so it travels that you can’t see traveling because it travels and then it attracts the to black and it would catch to black it would like to stay onto black I guess because it's black. (Students giggling)

Student: I think I think I disagree with what I believe in that uh the light was exactly the uh—

Teacher: So you disagree from what you said earlier, you mean?

Student: Yeah.

Teacher: Okay.

David: because um I I think that the air is like heat because like a heater uses the air, it heats it up and the air travels around the house to heat up the whole house.

Student: I dis

Teacher: And how is that different from what you said before?

David: Because I said that the heat is like

Wasolla: I disagree with David because

Teacher: By the way David, I think that so cool that that you thought something else and your ideas changed and you were able to express that. That's really — that's neat—that that I like the way you’re thinking.

Wasolla: I disagree with David what he said about air being heat. Because air can sometimes be cold.

Student: But

Student: No but

Student: Yeah but heater—we have a heater

Student: Not but that

Student: Heater, we have a heater

Student: That’s that’s

Student: We have a heater thing in our house and you can turn up the temperature.

Student: Yeah, that’s what everybody has

Student: I. I didn’t say that.

Teacher: Let’s listen to David one more time, Listen up.

David: Wasolla, I didn’t say that the air is not—is always hot. I just said air is hot sometimes, so it could turn cold.

Teacher: What made you change your idea?

David: Because I thought of uh my dad working on the heater. Because my dad does heat. Heaters and air conditioners—and then I thought of the word in from the air conditioner—air? And then I thought that if air can be cold from an air conditioner, then why can’t a heater use air to make it hot?

Teacher: Well the heater uses air and air is what makes the heat—

David: Yeah.

Student: I thought is was always gas.

David: Yeah, because there’s like vents everywhere.

Teacher: So what do you think it is in the air that is making heat?

Student: Hmmm.

David: I think it is the light. I think the light is like heating the air up.

Student: I always thought it was like a gas or fire or something.

Teacher: What?

Student: The heat

Teacher: The heat, the gas or the fire?

Student: Yeah, not the light because if you have the dryer my mom always tells me to keep stuff away from the dryer because fire goes through there and it might catch on fire or something.

Teacher: Hmmm.

Brian: When I was up in New England, on our big ski trip thing, um I slept um on the floor ‘cuz there were only two bedrooms. And I was right near the heater and my mom told me not to put anything near it or like it was an electric heater down on the bottom and my mom told me not to put anything near it or inside of the because it’ll catch on fire.

Teacher: Hmmm

Student: If you put paper near it, you know it can like burn it.

Teacher: Ok, so there's something going on that can do that. Um, let's get back to let's let's continue where we’re going with this idea of light and heat and how heat is created and so forth. I like what you what you're thinking.

Student: I think that light, this is um I'm kind of changing my mind, I think light is kind of light a comet it's going so fast like is burning up into heat it's like going so fast it's turning into heat. So when by the time it gets down to earth its heat and you sometimes it's heat and not um

Teacher: What is that what you're saying?

Student: I think that’s kind of like what Seong is saying.

Teacher: kinda like what Seong was saying, yeah.

Student: [Unclear.]

Teacher: How many people think that you get the heat when light hits something, like causes heat.

Student: I do. I do. Me. I do. [Students mumbling].

Teacher: What do you think? Why do you think that?

Lisa: I think that sometimes, well, most of the times, light is not always containing heat. Like, like this light up here, it’s not con—it’s not, its not –

Dashawn: Burning?

Lisa: Yeah, like making you hot.

Kyle: Yeah it’s not making anything hot.

Anna: But it's just—what if you go up there and touch it? It would—?

Brian: That's because your finger is an object. When it hits something it’s hot.

Teacher: Oh, I see. So you get, there's a reaction when you touch light.

Brian: But it's also a question like, um, if a door slams— if a locker door slams and no one’s around to hear it, does it make a noise? Because you don't know if— if you don't touch it and the light is making heat and making the air hot. You won't know.

David: Yeah well how is, fine then put it this way how does the fire makes you hot when you're not touching it?

Brian: Because it's warm!

Student: Because that's a fire.

David: But it's still, it's the light source.

Student: Heat heat.

Brian: But when you say a lightbulb, a lightbulb doesn't really run on fire. It runs on electricity.

David: I know! I thought it [?] but it’s still a light source.

Student: I—its because its wood. Wood catches on fire like paper so when you eh—wood—if woods are made out of tree trunks.

Student: Woods? Woods?

Student: Wood. [?] Tree trunks

Teacher: Like a piece of wood.

Student: Yeah, um, it’s made into paper sometimes, and when you put that together with like newspaper and you light it, um it forms a fire.

Teacher: So anytime you have light, do you have heat?

Student: Yeah.

Student: Sometimes.

Student: Not always, not always.

Student: I—I have a lightbulb and it gets really hot because when I when I put it inside a diff..because it’s a different kind of light bulb so it gets really hot and that’s not what usually lightbulbs do. They just get not hot its just..

Student: There’s different light bulbs for different purposes though.

Student: I think—. Like outside its its light its light outside but its still cold outside, so light doesn’t always get hot, get you heat.

David: Yeah but that that is could be like the angle that the earth is at. You could you never you could always think of that.

Brian: Remember when we learned about

Student: Yeah but it’s the light is not um solar

Brian: The light. I mean the sun and the earth

Student: I kind of agree with [?]

Brian: I don’t think it’s the angle. (Teacher: shh..) Remember when we learned about light. I mean, the sun, the earth, and the planets, its like, what the an..what angle the earth is at. And what angle the sun is at.

Student: Well the sun doesn’t turn.

Brian: What angle the earth is at.

Student: And sometimes where the moon is.

Student: We have the earth is rotating in the front.

Student: Like rotating [?]?

Student: No it's revolving

Brian: Like right now we have winter and Asia, right now, or in China or (Student: California) over there over on the other side of the world, um they're having summer over there right now.

Student: Like Australia

Student: Yeah

Students: [Mumbling.]

Student: California‘s not the other side of the world.

Student: But they have different kinds of life over there at [?] And they do different things and have different colors.

Student: They can last longer than the other [?]

Student: No they don’t

Teacher: So does it have to do with the angle of the lens?

Student: Yeah, yes. I agree.

Teacher: So when we set up our solar ovens do we have to put them at a certain angle in order to create heat?

Student: Yes.

Student: Remember when you were talking about light [?]? and you drew a diagram on the board and we had for our warm up?

Student: Well maybe it would be different. I think the angle would be..dot the angle would be the light and the boxes right here then the um the foil and right here so it would hit the foil and then come inside the um solar ovens.

Student: Because if it's if the light is facing the other way then there wouldn't be, it can't just go around over the foil and then hit it and then go back in.

Teacher: Frankie and then Kyle

Frankie: [?] I think it does have something to do with the angle because when we were doing that experiment with Miss Viglioti it um each angle got a different temperature like direct got the highest and then [?] and then the shadow.

Student: [?]

Kyle: It depends on how close on how close the heat is to the solar oven.

Teacher: That's kind of similar to what Brian was saying, that it depends on how far the Earth is from the sun. [?] Ok, I notice that some of you are getting a little antsy. What—moving around a little bit. Um—let’s kind of back this up a little bit. Let’s wrap it up with any final thoughts about what we talked about today.

David: Um..I remember somebody saying that the sun and like a light bulb has like different kin..ah..heat like different temperatures of heat. But I don't remember who it was. So ahh.. But I think that since the sun is so far far away from us like the lamp would be like close to the solar oven then like they’re around the same temperatures.

Student: I thought that

Student: The sun and the in so— and the light, the sun and our light bulb would be at the same temperature?

Student: No, not really.

David: Like um the sun's really powerful and it hits us, right? But it's not on its full capacity because it, the light travels all the way over here so if the light bulb is like weaker than the sun and it's closer to the uhh solar oven then I think that they would be around the same area of temperature.

Appendix H

Transcript 8

The following transcript is from a 5th grade classroom. In a discussion about falling objects, the students were using the word “gravity” to explain their reasoning. Curious about what the students were imagining gravity to be, the teacher asked “what’s this word, gravity?”

Teacher: What’s this word gravity? That’s another big word. We use that word a lot. What does gravity mean?
Ibrahim: Like, like if I throw this pencil up in the air, like it pulls it down with strength.
Teacher: So gravity is a pull?
Ibrahim: Yeah.
Student: No
Ibrahim: If we didn’t have gravity, then…
Teacher: Gravity is a pull downward.
Ibrahim: Yeah
Teacher: Pulls things down. [Several students start dropping pencils] Anybody want to…
Student: It speeds up.
Teacher: … agree with that or challenge that? Theodore.
Theodore: Like um, gravity is like when you are like in space and um then like when you are trying to punch like um, somebody and your hand stops like that, because you go and go slow, first and second.
Teacher: You go slow in space?
Theodore: Yeah, you go slow in space.
Teacher: Why do you go slow?
Theodore: Because space like um, space has too much high gravity
Teacher: Space has a high gravity.
Theodore: Yeah. Which which lets you, you walk slow, you punch slow, or you can do everything slow.
Teacher: Um, anybody else? Julie.
Julie: Remember when he said, the last thing I remember is that you said that if you throw a marker in the air, it had the possibility of going down or the possibility of going up? Only that it would go up a little while then it would come back down.
Teacher: What does that have to do about gravity?

Julie: Huh?

Teacher: Huh?

Julie: That, it could (??)

Teacher: Does gravity making it go up, or does gravity make it come down? What's happening? Gravity making it go down. Okay. Uh, Thimios.

Thimios: I have two things to say.

Teacher: Okay

Thimios: First of all, space has a low type of gravity.

Teacher: Oh, so you are disagreeing with Theodore?

Thimios: Yeah, because, right there [written on the board], it says gravity pulls downward. In space, it is like it just flies. And about like the circle thing, you can balance it. But it is like, it concentrates on the middle. (??) balance.

Teacher: So you are saying if it, if it a sphere on a flat surface, it is easy to make it move.

Thimios: Yeah, because it's concentrated.

Teacher: Because the gravity is in the center, the gravity is on the middle. But if it was on a curved surface, and it fit inside, then what would happen?

Thimios: You would have to like pick it up and throw it.

Teacher: It would be harder to make it move and roll. Okay

Thimios: [??]

Teacher: Theodore:

Theodore: I disagree with Thimios.

Students: [laughter]

Theodore: I saw a movie, a movie where two people were talking about space, like um, like um, they look like, what's the name again?

Students: Astronauts

Theodore: Yeah, astronauts. And um, they said that they had a really high gravity. Gravity, like um, like one day I watched a cartoon called Jackie Chan Adventures. [Students laugh]. Um, They showed when he was about to punch a man. And then his hand moved so slow um

Teacher: He was in space?

Theodore: Yeah, he was in space.

Teacher: All right, we can talk about this. Let's talk about space and gravity. We have two opinions. One, that space has a

Ibrahim: low gravity

Teacher: A low gravity, or a less gravity than Earth. And the other one is that er space has a lot of gravity. And Theodore says that space has a lot of gravity and that's why everything moves so slow[ly]. Thimios says that space has a little bit of gravity and that's why if you jump up, you would just keep going up and up and up. Right? [Thimios shakes his head yes and raises his hand] Let me hear someone else before besides these two then I will come back to these two. Okay. What do you guys think? Uh, Felix.

Felix: Well, I think there is less gravity, be, if, if, you throw something in the air you know it's going to come back down because gravity um, pushing it down.

Teacher: Here on Earth?

Felix: Yeah.

Teacher: Uh, huh.

Felix: And if we're in space, there's less gravity, we'd be flying up and jumping (??)

Deena: I agree with Thimios just because well that that's why if you threw a pen or anything in the air, it would fly down really fast because of the gravity. It has a high gravity here. And in er, in space, if you jump up, you would just like keep going up in the air because you have a low gravity.

Santiago: Uh, I kind of agree with Theodore because like the sun it has like enough gravity to keep us from spinning around in orbit.

Teacher: So gravity comes from the sun?

Santiago: I think, I don't know.

Teacher: Well, why do you think gravity, lets, why do think gravity comes from the sun?

Santiago: Because it, keeps other planets from rotating around it.

Teacher: Okay, so because planets rotate around the sun, then gravity must be, the pull must come from the sun. Because it [the sun] stays still and the other planets are moving? That's your theory?

Santiago: I don't know.

Teacher: Fine. Okay. Lorenza

Lorenza: I have to agree with all of them, because like

Teacher: Even, both of them?

Lorenza: Yeah.

Teacher: Okay.

Lorenza: When you walk, you walk slow, but you can talk slow, jump and just stay.

Teacher: Here, on Earth?

Lorenza: No, in space

Teacher: Oh. So, that supports what theory? That there is a lot of gravity or a little bit of gravity?

Lorenza: Like, like half.

Teacher: Half? Oh, so not a little bit, not a lot but some.

Lorenza: Yeah

Teacher: Julie.

Julie: I agree with, um, (??) if you go up and jump up…

Teacher: That means a lot of gravity or a little bit of gravity?

Julie: Um, a little bit of gravity.

Teacher: Okay.

Julie: Um, if you go up and (??) up and down, that (??) there is still(??)

Ibrahim: I agree, I disagree with Theo because um, when you're going in space and jump on the moon, you jump back up you stay um, um in space you don't move anywhere, you don't come down. But on Earth, if you try to jump, you come straight falling back down, so I think um, space has a lower gravity, and and Earth has a higher gravity.

Teacher: Okay. Cristian.

Cristian: Um, I agree with Theodore because, um, like, gravity makes you slow. Um and (??) in space walking like slow and like to the space shuttle, you have to walk slow, and like, it's like (??) it feels like you need to be so strong, it feels like it is hard to walk or something.

Teacher: So what does that mean?

Cristian: That it has to like be strong to walk…

Teacher: So you agree with Theodore.

Cristian: Um, huh

Teacher: Okay, Khawar.

Khawar: I think in space there is a low center of gravity because like

Teacher: Low center of gravity?

Khawar: Well, like less gravity (??) In space when you go up, you stay up, but um in Earth, there is more gravity like because when you jump up, the gravity pulls you down fast, so I agree with him.

Ibrahim: Um like I think um like um Santiago is right when like he said the sun like has it pull the earth and the planets together. But like if you're, um, um I think that he was right because how come the Earth is not moving away from the sun.

Teacher: So because the Earth is not moving away from the sun, you say that the gravity is coming from the sun.

Ibrahim: Um hum

Teacher: Okay, ahh. Who did I say was going to be next?

Lorenza.

Lorenza: Um, I was going to say that um, I kind of, um I still kind of agree with him, but um, but um (??) said, but um, but um that when we go up in the air (??) I think that we just will come down slowly.

Teacher: You think that he will come down eventually.

Lorenza: Yeah.

Teacher: But, it just takes a longer time. But does that mean more gravity in space or less gravity?

Lorenza: I am not really sure.

Teacher: Don’t know, okay. Thimios.

Thimios: Can I do a demonstration?

Teacher: Sure

Thimios: If gravity is pulling down, right.

Teacher: Um, hmmm

Thimios: So if you were doing (??) punching going like that, it would just [he makes a slow motion downward punching movement] it would go to the floor.

Teacher: Where?

Thimios: In space because its, because gravity going downward.

Teacher: Uh, huh

Thimios: So it’s like that. When you try to punch (??) and because you’re going so slow, it’s because when you go to space. It’s because your weight is divided by three. So it makes you weaker, kind of.

Teacher: So I would weigh one third less in space, or one third more?

Thimios: One third less.

Teacher: That’s a good diet. Let’s go to space. [laughter] Okay, Kevin.

Kevin: I agree with Theodore, because um, when I was watching this cartoon, when the gravity went up, when they were playing, it was harder for them to to move faster.

Teacher: Okay. So. Because it was harder for them to move, you think more gravity. That gravity makes it harder for you to move. Okay, ahh, lets have Deena.

Deena: I now agree with Theodore.

Teacher: You changed your mind?

Deena: Well, cause look it’s, it’s like, this has low gravity, (??) never mind, never mind

Teacher: Go ahead

Deena: No, never mind.

Teacher: Okay, Kenny.

Kenny: I agree with Theodore because um, um sometimes in space, um you weigh lesser than you would, so if it’s like um, it’s like as if you um were on a bungee string or something like that, and it’s like the moon or something.

Teacher: What about the bungee string, moon?

Kenny: It makes you like go, it’s like um it makes you jump higher, but

Teacher: What’s it? What makes you jump higher?

Kenny: The bungee thing or whatever.

Teacher: You would jump higher in space or on earth?

Kenny: Space.

Teacher: Because--?

Kenny: Because you going to weigh less. And when you jump it’s like you’re going to have times three of what you would jump here.

Teacher: Okay, um Felix.

Felix: I agree with Theodore and Thimios, because there is just a little gravity in space. And if you um, If you went up in the air, you uh would eventually come down because, um there’s a little gravity in space.

Teacher: So just a tiny bit, but not as much as here?

Felix: Yeah.

Teacher: Uh, Santiago.

Santiago: Uh (??) you said like that the sun or something like that the gravity pulled in a like a comet, or asteroid (??)

Teacher: Okay

Santiago: [??]

Teacher: So what are you saying about where gravity comes from?

Santiago: (??)

Teacher: You still don’t know? But somewhere there’s gravity pulling some things in space closer to earth, like asteroids and comets and stuff.

Santiago: Yeah, and like the moon

Teacher: The moon

Santiago: Yeah, it like (??) it controls like (??) the waves and so that makes like tidal waves, so that means the moon has gravity.

Teacher: So the moon has gravity and that causes waves and tidal waves.

Santiago: I think.

Teacher: Okay, Julie?

Julie: Um, I think um that in space, um, when you try to turn around in space, it takes a little long, and that’s what happens to the Earth when it tries to rotate, that;s why it takes twenty-four hours, it takes a day to rotate one whole turn and maybe um maybe there’s um that’s why (??) the earth has low gravity in the air.

Teacher: A little gravity

Student: Low gravity

Teacher: Low gravity or high gravity

Julie: Um, low gravity.
Teacher: Theodore thinks there’s high gravity.
Julie: Then I agree with Thimios.
Teacher: You’re agreeing with Thimios. Okay, ahh, Khawar.
Khawar: You know what Kenny said, he said like he said that you could loose weight when you go to space and um that’s what he (used or knew). And he said that he agreed with Theodore like when you use something, that Thimios (?)
Teacher: All right, Thimios.
Thimios: I just want to say something. Cartoons are cartoons. They are not real life, okay people.
Santiago: What do you mean they are not real life?
Thimios: Gravity is the a pull downward. (??) They’re saying gravity, they’re saying gravity is a pull upward! It is a pull downwards. Those comics are wrong. They’re lying because there is not a lot of gravity. So they are going up and space and they are not falling down. Because there is no gravity there.
Theodore: I disagree with Thimios.
Students: [a lot of laughter and noise]
Teacher: I can’t hear. Go ahead Theodore.
Theodore: I saw a movie, “The Matrix” and how come they do that stuff and um
Students: It’s a movie! (??) Shh!
Teacher: Lorenza
Lorenza: I tend to disagree with Theodore because they could be using a harness and pulling on wires.
Teacher: You have seen them do stuff like that in a movie before with a harness?
Lorenza: Yeah.
Teacher: Deena.
Deena: I kind of agree with both of them, it’s because like when I go in the water it’s like I can carry like when I go into the water, it’s like you loose a little weight cause like my little sister like her, she really can’t pick me up because I am really heavy and when I am in the water, she can pick me up.
Teacher: So what does that say about gravity?
Deena: I don’t know, it’s like. I don’t know.
Teacher: Are you connecting? Does anyone know why she said that? Rebecca.
Rebecca: Um, I think she saying this because, like if you are in the water, you are still staying down in the ground, but once you are in the water you feel like you are loosing gravity of yourself.

Teacher: And what did you say?

Rebecca: [??]

Teacher: So being in water is like being in space? Why?

Santiago: Because it is more easier to pick up a rock in the water and in space.

Teacher: So, it is easy to pick up heavy things?

Deontrae: No it's easier to pick up heavy things in space.

Students: (??) water makes it lighter, yeah.

Teacher: So is being in water and being in space similar?

Students: Yes. (??) No.

Teacher: Ah, hah one at a time, one at a time. Julie.

Julie: I think it is similar, um because um, water, you go into the water, you could um, you could kind of loose weight. You can push the water up.

Teacher: Why do you say loose weight? Explain that to me.

Julie: Because if you like um you're not, you're not like on Earth. On Earth you could just touch the water and pick it up like this in your hands, and then it will fall out though. But when you're in the water, you can just push the water off you, it's like, um heavy. It feels like you lost weight or something.

Teacher: Okay, Santiago then Deena.

Santiago: Like when you are in the swimming pool and like when you reach the bottom and then you can jump up high, from the bottom. That' kind of like space.

Teacher: Why is that like space?

Santiago: Ah, You can jump up high.

Teacher: Because you can jump high. Ah. Deena.

Deena: And it is kind of like what Thimios said. Because it's like. That's why it is really hard to walk on, that's why is really hard to walk on water like on beaches. That's why, it's like sometimes it's hard for me to walk on the water in beaches.

Teacher: So, it's hard for you to walk in the water like it's hard for you to walk in space.

Deena: Yeah, you have to, yeah, yeah.

Teacher: Ibrahim.

Ibrahim: I think water, um water, is the same as outer space because like when you are walking on the water, it's like gravity is pulling your legs down.

Deena: Yeah, it's hard.

Ibrahim: It's like, when you're walking like I went to um Ocean City, I went into the water, the water pulled me down.

Teacher: Um hm. Okay, pulled you down like what?

Ibrahim: Like, like gravity is pulling me down. And when I went to the sea, close to the sea, the water was pulling me down still, kind of.

Teacher: Thimios.

Thimios: The water, I think it has like a medium center of gravity, because in the water you gain weight. You know, because it is harder to move and everything.

Teacher: So some people, so you are disagreeing with the people who say you loose weight. You say in water you are actually heavier?

Thimios: Yeah, because you have to, because you have to like if you try to walk in the water, you walk like this [he takes steps with a long stride].

Teacher: Like slow motion?

Deena: Yeah, it's hard.

Teacher: Okay

Student: And (??)

Thimios: And, you know, it's hard to pick up things in the water.

Deena: Actually, it not. Actually, it's not. It's light. It's really light.

Thimios: Well, if you tried to pick up like a big, big rock,

Deena: It's light.

Deontrea: It's light

Students: (??)It's real, real light. You could pick it up easily, with your hands.

Thimios: But then it wouldn't weigh so much. But in the water it gains weight.

Deena: Actually, it doesn't

Kenny: No it doesn't. It looses weight.

Students: (??) [Many students talk at once.] I know.

Thimios: Water has pressure. Water has pressure. Remember the Ranger Rick magazine we read? It said (??)

Student: Shh.

Thimios: Water pressure makes it hard on you. So it's like you have to like use all of your muscles to [many students start to talk]

Teacher: So you are saying because of the water pressure, the water has pressure, which makes it hard for you to walk.

Thimios: Yeah.

Teacher: Okay, ah. Felix.

Felix: Ah, ah, I think that uh space and water, kind of similar because except space you would jump up in the air and if you're down in the water sometimes, you would, um float back up if you are um, I don't know.

Student: Oooh!

Lorenza: Um, I kind of agree and disagree with Thimios because like it’s like the rock (??) right, but it would be hard to pick it up because the rock, the water gives a lot of pressure on the rock. So

Teacher: What do you mean the rock looses weight. Explain that?

Lorenza: Like, it is kind of like it is lighter, below the water, like when you go to pick it up. It won’t come up because the water gives a lot of pressure on it. (???????)

Teacher: Khawar. Julie

Julie: The reason why the rock in the water because Earth, when throw it on the ground, it will, um, land easier because of the gravity, but when you throw it on the water, it takes longer for the rock to go down to the surface. Because how, how, how heavy the water is and how much pressure it is on it. And because the rock is also heavy. And that the weight of the water, it can just push it down. (??) But on Earth the air is pushing it down and the air doesn’t weigh anything, so it will just push it down to the ground.

Teacher: So the rock is pushing So you are saying that the rock moves slower in water not because of gravity, but because of the water pressure? Is that what you are saying?

Julie: Um hmm.

Teacher: Okay, so you are saying that the air doesn’t have a lot of pressure so the rock falls quickly. Santiago.

Santiago: It’s not really like you are getting heavier, because all of the water around you is making you harder to move

Teacher: So you are not gaining weight.

Santiago: No

Teacher: Uh, Ibrahim, Thimios and Theodore.

Ibrahim: I agree with Lorenza like earlier what she said because she said um, like um, um like. When you’re in space you fall down um like it takes a long time to fall down. So like, if you drop something in the water, it’ll try, it floats up slowly. So I think water, and um outer space is similar.

Thimios: Can I do a demonstration?

Students: Uhh!

Thimios: Pretend you are a little green person with a little tiny body. Everybody is saying that gravity is here or that Earth has a lot of gravity (??) or gravity is coming down to you. It would be harder to pick something up in the water because gravity is pulling you down here, like that.

Teacher: So you are saying not only do you have to pick up the rock, but you have to fight gravity pulling the rock the down.

Thimios: Or pulling the rock up

Teacher: Gravity pulls the rock up?

Thimios: No, gravity pulls you down but

Deontrae: Gravity does pull the rock up.

Thimios: That’s why the rock will be weighing more. The people will be weighing more because, gravity is pulling down the rock.

Teacher: Okay

Thimios: That’s what everybody is saying (??)

Teacher: Do you agree with that or disagree with that?

Thimios: I agree that the gravity is pulling you down. That’s the only thing I agree with these people.

Teacher: Okay, Theodore.

Felix: I’m confused.

Teacher: Oh well, Thimios is saying that when you try to pick up a rock, gravity is pulling the rock down, and you’re trying to push it up. That’s why it’s hard. Because you have to fight against the weight of the rock and gravity. Yes? Thimios is shaking his head yes. Theodore.

Theodore: Thimios said that the rock that the water makes something heavier. How come like when we put a beach ball in the pool, and so, and and then we push it down and

Teacher: It goes under the water.

Student: Shh

Deena: Yeah!

Theodore: It pops up really hard and um it may hit your face like pow!

Teacher: So, it pops up with a great force?

Felix: Yeah, it does!

Thimios: It’s because it’s light. It doesn’t weigh anything.

Theodore: Basketball too!

Deena: It has air inside.

Thimios: A basketball only weighs four pounds. (??)

Theodore: Four pounds is heavy!

Felix: Ohh!

Thimios: [??] only weighs five pounds. It’s going to jump up and gravity is going to pull it down when it is in the air.

Appendix I

Transcript 9

This transcript is from a second grade classroom. The teacher has brought magnets and is asking the students how do magnets "work?" One question related to this is concerning the ability of a paper clip that is touching a magnet to then pick up another paper clip. The transcript begins with a discussion regarding this.

Dalton: Well if it's third (the paper clip) then, um, it would definitely pick the whole thing up.
Teacher: Why?
Dalton: Because um it's um takes a lot of um it would take about two magnets to get put together to get- hold a rock up. Hold a rock. And put two paper clips on— and he said he put it third and then he put the paper clip on the bottom and then picked it up and um um it can't get very much magnetism through it because it's just two little small paper clips.
Teacher: Okay, so you're, are you saying there's not enough power in one of these?
Dalton: There's enough, um, electric power in it but um it just couldn't hold up the rock because it doesn't take very much.
Teacher: Okay.
Dalton: It doesn't, 'cause, um, because um the power the magnet takes a little bit of power through each paper clip and um, it goes right down into it. And um, the rock's heavier than it so it would have to fall off.
Teacher: Okay so you're saying that what Calvin described can't happen because the rock is too heavy?
Dalton: Yes.
Teacher: But you also said that some of the power or whatever goes through the paper clips—is that true?
Dalton: Yeah but um if you've got a rock, it's hard to put a rock on because some rocks aren't made of metal.
Teacher: Okay, Calvin do you want to—?
Calvin: Um— well, when I pulled it up I held it from the magnet and the rock so it wouldn't fall down.
Teacher: Oh, so you were holding.
Calvin: The second time when I hold the rock.
Teacher: Because the first time what happened?

Calvin: Yeah, because the first time all I did was pick the magnet up and it went fweep!

Teacher: Okay. So when you did the experiment again you held the magnet here with the paper clip and then you held this rock and there were two paper clips hanging off the bottom of the rock and that worked—the paper clips hung off of the rock. Okay, what do you think about that, Dalton?

Dalton: Um it would only be possible if um you got the magnet and you stuck the rock on first.

Teacher: Why?

Dalton: Because the magnets are smaller than the rock and it, the rock takes more power into it so you can put three paper clips onto the bottom and pull it up without it dropping.

Teacher: Okay so does the rock pull something away from the magnet?

Dalton: Kind of.

Teacher: Kind of. Okay. Renee.

Renee: I think there is clay inside of it because clay does pick stuff—things, like paper and stuff.

Teacher: Okay, so if there's clay inside here, does that help it stick to things? That helps the magnet stick? Okay, does it stick to paper, like clay does?

Renee: Ummmm.

Teacher: Okay, so the clay that's in here that you're saying is in here- what does it help the magnet stick to?

Renee: Metal.

Teacher: Okay. So is it—? Why does that work? Because if I have clay and I can stick it to paper, but I can't do that with this?

Renee: I mean if the clay was like [?] it could stick to paper [Teacher: Okay okay.] And something that's metal then it can only stick to metal.

Teacher: Okay. Alright. Go ahead Taylor.

Taylor: Um I have a different one. Yesterday when we were at the science Saturday we saw a reaction when this guy poured an um really cold water and then he put food coloring in it and he um, added— I forget what it was called, but when it put it in it got all bubbly—

Teacher: Very cool, very cool. Kind of different from magnets, huh? Okay. Alright. How about over here at this table? Do you guys have anything you want to add to this power idea? Go ahead Evan.

Evan: I agree with Taylor about the little magnets inside the big magnet. Because, um, a couple little magnets can stick to anything.

Teacher: Okay, so you're – you're saying there are little magnets in here and if there's a couple of them in here that's going to make this stick?

Evan: To most anything.

Teacher: To mostly anything, okay. So – where is this power stuff coming from? Go ahead Carla. Oh I'm sorry is there something else you wanted to say?

Dalton: I don't understand!

Teacher: So don't I!—go ahead—

Dalton: Because Evan said um well—I was thinking in my head when he said that there's magnets inside there—what are in the other—what are in the magnets that are inside the big magnet?

Evan: Ohhh.

Teacher: OOOH! Uh oh! [laughter] [talking] Let me – let me make sure I'm understanding Dalton correctly—let's put this back out on the floor here—hang on, hang on for a second here. Evan says there are little magnets in here and you were agreeing with Taylor- right? And Dalton's question is: Okay, well if there are little magnets in here making this work, then what's inside the little magnets? Okay—that's what he wants to know [so do I!], that's his question to you Evan.

Evan: Little pieces of metal.

Teacher: Little pieces of metal?

Dalton: Then what's inside *them*?

Student: Yeah- what's inside the little pieces of metal?

Taylor: Clay.

Teacher: Oh Taylor has an answer, she says clay.

Student: Clay?!

Student: And what's inside of clay? Play-doh!

[Laughter.]

Teacher: Now wait a minute, wait a minute, we've got this magnet and we're breaking it down into smaller and smaller pieces, but then how does that make it work—if that's really what in here, we work our way back and way say okay: clay, bits of metal, little magnets, big magnet: how does that make this magnet work?? I don't know!? Ben?

Ben: I disagree with Evan because last time (??) a piece fell off and there wasn't any little pieces inside.

Teacher: Oooohh—. At the very end of class last time I was talking to some folks over here and we took two of these and they went—fwwp- they smashed into each other and a piece broke off and Ben is saying he saw that and he says there wasn't a little magnet inside. Hm. What are you thinking Taylor?

Taylor: Because it was just blended in with that magnet because most of them are in the same color.

Teacher: Oh, so when this broke off—

Taylor: There (?) the little pieces.

Dalton: Then how could they- then how could they be so close together that you couldn't even see the lines in between them?

Taylor: Because they were glued.

Dalton: Well glue makes 'em fatter.

Taylor: There was clay on top of em

Student: Nuh uh clay's —

Dalton: Nuh uh clay's not that black!

Teacher: Hang on—[Savannah: There's food coloring.] Savannah's — with food coloring. Okay.

Dalton: Food coloring!

Student: That would be [unclear: very weird?]

Teacher: Hang on for a second—Savannah.

Savannah: You had um if there were magnets inside the – those magnets it would be really fat! It would be fatter because the little magnets are as thick as that.

Teacher: Okay so you're saying this is too thin to have little magnets in it—if this really had little magnets in it it would be fatter? This way? Okay [nuh uh] okay—Calvin.

Calvin: I disagree with Taylor and because well I think that there's um. That there's um just the magnet the magnet is just there. You know? No other magnets.

Teacher: So there's there's This is it—it's a magnet, there's nothing inside except "magnet"—the, whatever this is?

Calvin: And the electricity's in the magnet.

Teacher: And the electricity. Alright- let's get back. Wait a minute, hang on for a second—hang on for a second. Remind me about the electricity. I'm going to come back to that—yes?

Student: I am confused with Taylor.

Teacher: About what? Be specific what are you confused about.

Student: What she said before um Calvin was talking—

Teacher: You mean about the clay inside?

Student: Yes.

Teacher: Okay—do you want to add on to that?

Taylor: Um—I don't know what she's talking about.

Teacher: Okay. Hang on—let's see if we can figure this out. I've got hands over here going off too. Emily?

Emily: I have a question [go for it] um um what is metal? If that's metal – what's inside it?

Teacher: There's a question: if this is metal then what's inside. What's inside—anybody have any ideas? Ben?

Ben: The um what's inside is like magnetite because magnetite made magnets so magnetite made magnets.

Teacher: Is this made of magnetite? [mm hmm] What's magnetite?

Ben: A type of rock.

Teacher: So this is a rock?

Ben: No. It's metal, because they made metal out of —.different kinds of magnetite.

Teacher: Okay, so this is metal, and metal's made out of magnetite—okay alright. Who wants to add to that?

Student: I agree with Ben because there's rock inside it.

Teacher: So there's rock in here? This is metal and there's rock inside? What do you think Emily?

Emily: How do you know there's rock inside?

Teacher: Renee? How do you know? How do you know if there's rock inside? [I have a question] Katie? Not sure? Dalton.

Dalton: Um—there can't, there could be some metal on rocks because um we have um a park (?) right off of our lane it's inside and I like to pick rocks up and throw 'em and I saw some that had metal on the side of them.

Teacher: Okay how does that relate to magnets?

Dalton: Because magnet—it's kind, because magnets are made out of metal and it had stuff kind of like metal.

Teacher: Okay so the rocks you found had something kind of like metal and that makes them kind of like magnets?

Dalton: Yeah—it had the same kind that they use for magnets.

Teacher: Okay—Michaela?

Michaela: How do you know there's [?] metal inside?

Teacher: I dunno—that's a question for you guys—how do you know there's metal inside? She – Michaela asked a question, how do we know what's in here? Yeah—Emily how do we know there's rocks in there. Who's got some ideas? Carla?

Carla: I think there's metal in there because if there wasn't metal in there it would it [?] metal around the outside and it probably wouldn't pick up metal that well.

Teacher: So it has to be all metal or it wouldn't stick?

Carla: Mostly metal.

Teacher: Mostly metal. Okay.

Student: I know there’s clay in it because I went on this website about magnets and it said that there’s clay inside.

Teacher: Hm—okay. So, go ahead. Taylor.

Taylor: I — um agree with Ben because that’s a rock it’s just they shaped it into a rectangle.

Teacher: Oh, okay! so can I go out on the playground and make it do the same thing that this does? [Students: No no no.]

Dalton: I’m confused.

Student: That’s a special kind of rock.

Teacher: Okay so I have to find this special kind of rock and that will work like this does. How are you confused?

Dalton: Because um I’m confused by how do they make the rocks square? They just get a machine and they push it flat and they push it sideways?—

Teacher: Can I toss Calvin’s idea back out here for a second for us to discuss?

Student: I don’t even know what it was—

Teacher: I do. He brought up electricity. He said this is a magnet it’s only a magnet there’s nothing in it except electricity.

Calvin: Electricity and the magnet.

Teacher: Electricity and the magnet. Alright, what’s electricity?

Calvin: What I meant was whenever it attracts metal, we can’t see the electricity going to it—except we can feel it since it’s pulling.

Teacher: So if I have two magnets or a paper clip and a magnet? Which one?

Calvin: Either one.

Teacher: Either one—I can feel something pull it. Okay and you’re saying it *is* electricity or it’s *like* electricity.

Calvin: It is electricity that pulls them together.

Teacher: It is electricity. Okay, so then my question is: what is electricity? Dalton?

Dalton: [Pointing.] That’s electricity! The light!

Teacher: That’s electricity—alright—is that what’s in here? What’s in here? What’s making this work?

Dalton: It’s wires!—[Students: Huh? What? Wires]

Teacher: Okay—hold on a second I think your classmates are asking you what do you mean by wires? [yeah]

Dalton: Um they have—you know how they make machine—cut a wire, it shocks you when you touch it? And um I tried it with a light bulb in the bathroom. [laughter]

Teacher: Okay—so you hooked a wire to a light bulb?

Dalton: No, I touched it and it um shocked me.

Teacher: Okay, what does that have to do with my magnet? Are there wires in here?

Dalton: It's kind of like it—they used wires to put it in that' why um some of them have little holes left from it—I've seen em.

Teacher: Okay- so to get stuff into the magnets— [what stuff?] I don't know that's what I'm trying to figure out. Wait a minute—Dalton, finish your thought—

Dalton: Um—it's kind of like it takes the electricity from the wires and plugs it in and then there it's a wire. A big long wire. And then they push a lever up and hit on and then um the electricity flows down from a big huge um—I've seen on tv—it has this big wall on the top and electricity comes down and it goes into the wire like this. And the magnet and then um it has um a certain kind of electricity.

Teacher: Okay, so to make this magnet work somebody hooked it up to a wire pushed the on switch, stuff came down through the wire to the magnet [electricity] electricity did—and now the magnet works.

Dalton: Mmm hmm. It's kind of like that—it's magnetism.

Teacher: It's kind of like that—you keep telling me that—it's kind of like that.

Dalton: Well it's not kind of like um—electricity. It's magnetism that flows down—

Teacher: Okay, do I have to plug this in to a wire?

Dalton: No—when you're making it.

Teacher: When I'm making it I have to plug it in. [yeah] and give it magnetism. [yeah] okay. who else has some thoughts on that process—Savannah?

Savannah: I have two thoughts on that.

Teacher: Okay—go ahead. Be nice.

Savannah: Make up your mind already! Between it kind of has something—

Dalton: That's hard to do! [Okay.] It's hard to do both at the same time!

Teacher: Okay so Savannah what's your question. Specifically what's your question—what are you confused about—you're saying make up your mind Dalton. Between what and what?

Savannah: Kind of and it is. Or it isn't.

Teacher: Okay—so you're saying— is your question to Dalton: IS this electricity or is it kind of like electricity? [Yeah.] Hang on—don't answer yet—yes?

Student: I remember that one time in this classroom you did—we had two magnets and we put them in front of a car [yeah and what happened] and then one side it would push the car away and one side would pull it together.

Teacher: Oooh—so how'd that happen?

Student: Electricity.

Teacher: Electricity—okay. [?] When you said the other side pushed it away—one side pulled it towards the other side pushed it away. Okay—so what's going on with that? Emily?

Emily: Well I am kind of confused with what Dalton said.

Teacher: Okay- can you specifically ask him?

Emily: Make up your mind—it's kind of the same what Savannah said, like, well, what what do you think in the magnet—because you're saying two things. Magnetism or electricity? What's in there?

Dalton: I can't figure it out—she's asking me questions and I make um a good sentences up, so they— they complete! Then—that's what Ms. McRae always tells us to do! Use complete sentences!

Appendix J

Transcript 10

?? what teacher what grade?

Teacher: Did you and your partner talk about what is happening when solar energy heats water? Or did you not get to that point?

Student 1: We didn't get to that point.

Teacher: You didn't? So, you all need more time. Brian?

Brian: Me and my partner, we thought that um what Brianna said—ahh—disagreed with her, that when—

Teacher: So you guys could have a debate back and forth?

Brian: But, when water would hit the top of it and spread to the bottom, send to put the thermometer at the bottom so it take the temperature at the bottom so that would have to be the temperature of the whole—of the water.

Teacher: Interesting. Okay. That's interesting because so far what I've heard from the group is that the sun's rays hit the water and travel down towards the bottom of the container.

Student 2: They spread out.

Teacher: I'm sorry, they spread. I need to use your words. They spread across, right? That's what you said.

Student 2: They spread all over.

Teacher: They spread all over. So, does anyone have any other ideas, or could you clarify that for me? What's happening? Anthony?

Anthony: Well, I had a new theory, um, when, the um, when—since the windows open, wind is coming in and it's cold outside, so that comes in, it makes the room colder, so that that makes that room temperature. Then, the sun is further away from the Earth now, so it won't really heat as fast with the [inaudible]—

Teacher: Miguel?

Miguel: I was thinking that—[inaudible]—from the top of the window, it's pointed up, so solar energy might come and go to—

Teacher: So, it might reflect off the window? Back up?

Miguel: Yeah, and then—

Teacher: Chen?

Chen: I have lots of things to say—

Teacher: Talk loud.

Chen: I kinda agree with Miguel, but I actually think that it is not really air because if you're, if the tall container is closer to the window, and solar energy might, it might have more solar energy than, um, the other container. And, I changed my mind and I disagree with him now, because the counter over there, it's not so hot because the leaves make some of the shade over there, and the leaves are blowing, so some of it, like, solar energy will come only like a little bit at a time. And—that's it!

Student 3: The taller container is partly in the shadow.

Teacher: Yes, I am noticing that the sun is not as bright at the spot as when we first came in.

Student 3: So the, um—

Teacher: —let's think about it as being the same—what if it was just, it was not changing. So, we'll still take the temperature of those containers, but I don't really have any other places in the room where there's a constant source coming through the window. So, let's just suppose that the same amount of sunlight was hitting both containers the entire discussion that we're having. I want to get back, one more time, to what is happening when solar energy heats water. Hunter?

Hunter: Well, what me and Brian talked about was when the solar energy heats the water, the water molecules are used to being like cold, and then when the sun heats it, they're not, it's not used to the heat, and then so the heat gets hotter.

Teacher: What do you all think about that? Andy?

Andy: Well, I think I get Hunter and I think I agree with him. Because, like, um, the sun is heating both containers and they pick-up the same amount of heat and they measure [?] to be the same temperature. And, I have something, I have, um, my Dad like makes coffee and heat puts water in, and puts it on the stove and since the fire comes up from the bottom it takes like two or three minutes to heat it up. But, since there is like no fire underneath them, it will take a long time for it to absorb the sun, and get it all over the two liters.

Teacher: So, he's saying that because it's not a source as, I guess as hot as fire hitting the container right there, it's going to take a lot longer for the heat, for the sun to, the water to absorb the heat?

Andy: Like, for instance, for example, if both thermometers said that the water was 73 degrees each in the beginning and it will take like one minute to go to 70-- or 75 degrees. So, it's going to take a long time to get to 100 or 90.

Teacher: And you don't think that the size of the container or the shape of the container matters?

Andy: No.

Teacher: Do you think that they would both heat at the same rate?

Andy: Yeah.

Teacher: —or they would both heat the same amount? Okay. We're gotten some new ideas about what is happening inside the container—to the water as the sun's energy hits the container, or it is collected into the container. Brian?

Brian: Um, I agree with Hunter, because since all the, it like stays out in the sun, and if it were hot, and more so, —[??]

Teacher: The water in those containers? Interesting. What do you all think about the molecules that Hunter's saying the water molecules—what's happening to those molecules?

Hunter: The water starts out cold, and then when the sunrays hit it, the water molecules, like, they're—they're used to being cold, and then the sun hits it, gets used to the heat and then the water gets hot.

Chen: They're cold, they don't really expand and when they're hot, they expand. When you boil water, it expands and there are bubbles on the top. And, you will notice that you start out with maybe half a cup, and it expands you get—it expands.

Teacher: I noticed that last night when I was making pasta. I had to turn the heat down because it was going to boil over. Sara?

Sara: Oh. Well, what I think is happening to the molecules when you put it down the molecules that used to the water, like Jennifer said, and then, now that the sun's not hitting them as much, now they are kinda like in the shade more. It's like, now they're like going back to like room temperature cause the sun stopped heating them to make them hotter anymore. The sun's making, like colder. Right now the shade's like making it a little bit colder. So, now I guess it's not quite room temperature, but maybe a little less than it would have been if the sun had stayed there.

Teacher: I have one last question. How does Hunter's idea, or Hunter and Brian's idea connect with Marianna's idea? Cause we—Marianna's idea was that the sun—the solar energy hits the container, hits the water, and spreads across—

Marianna: All over.

Teacher: —all over, spreads all over. As it travels down? To the bottom? Or not?

Marianna: Just spreads all over.

Teacher: As it just spreads all over where ever it can. How do those two theories connect, or do they not connect, or what do you think? Go ahead.

Student 4: Well, I think—Okay, this is mine, this is what I think. When a molecule gets like really hot and absorbs a lot, a lot of heat, and then it expands, some of the heat goes to the other molecule next to it, and then it goes on and on and on until the whole container's full of heat. And then they keep getting bigger and bigger and bigger. And the container keeps getting hotter and hotter and hotter.

Teacher: So that would kinda then explain what Hunter's—I think that kinda goes with Hunter's? Do you agree, Hunter? Do you feel comfortable with that? Miguel?

Miguel: I agree with cause, um, [inaudible]—

Teacher: Anthony?

Anthony: Well, I kinda agree with Marianna because, like, um, the molecules when they absorb the sun, it's like a person eating a lot and then getting fat, and then it spreads to the next one like a virus. And then it keeps going until the whole thing, until the whole thing's hot. But, when the sun's blocking, when the sun gets blocked, it's like an antidote to that virus, and certain, and the molecules get skinny again. And it keeps passing down on and on and then it gets cooler again.

Teacher: Excellent.

Student 5: I kinda believe the same because, since like the water molecules are all over, the heat spreads towards the bottom, then it's the same thing, and water molecules start to go up—[inaudible]

Teacher: Okay, I'm going to give you a piece of paper and I'm going to ask you to draw a diagram, with labels, so I can really understand it when I read it, of what you think is happening to those containers. And then below it I want you to write what you think about which liter container will have the higher temperature. They're both the same amount of water inside. Or, do you think it's the same temperature? Or do you think it would be the same? Even though, yes, our sun is kinda fading away.

Appendix K

Young Students' Analogies

Introduction

The analogies from student scientific discourse presented in this dissertation have been offered as evidence that analogies are based on schemas and are contradictions to an expected schema—a story consistent with the choice of the base in generated analogies, the multiple analogies and constructed analogies, and the same story that Lakoff (1987) uses to understand categorization. In the following sections, I present instances in which young students compare astronauts in space to being in a swimming pool, magnets to clay, and magnetism to electricity. In each case, the students display confusion with their own analogy. In one case, the student is not able to relate her analogy to the case at hand—that is to say, she states the analogical base but then cannot relate it back to the target. In another case, a student asserts a meaningful analogy but then confuses being *like* with being *an instance of*. And in the final analogy presented, the student explicitly grapples with the question of "it's like or it *is*." I argue that when these analogies are analyzed with respect to representational redescription, dual reference theory and semantic field theory, a story consistent with categorization emerges. Structure-mapping and other theories that limit analogies to pairwise analyses of the target and base would not predict and cannot account for the confusion young students show between statements of class-inclusion and statements of superordinate-class-inclusion.

Space as a Swimming Pool

The following transcript is from a 5th grade classroom. In a discussion about falling objects, the students were using the word “gravity” to explain their reasoning. Curious about what the students were imagining gravity to be, the teacher asked “what do you mean by this word, gravity?” In discussing this, some students claim that there is *more* gravity is space—a claim that the teacher (and this researcher) finds surprising. A student explains that in space it is difficult to move. Arguments against more gravity in space include the astronauts’ ability to jump high. During this debate, the Deena presents an analogy to reconcile the competing ideas but cannot explain how this analogy relates back to gravity or the arguments that preceded:

> Deena: I kind of agree with both of them. It’s because like when I go in the water, it’s like I can carry like when I go into the water. It’s like you lose a little weight. ‘Cause like my little sister, like her, she really can’t pick me up because I am really heavy and when I am in the water she can pick me up.
> Teacher: So what does that say about gravity?
> Deena: I don’t know. It’s like— [pause] I don’t know.
> Teacher: Are you connecting? Does anyone know why she said that?
> Rebecca: Um, I think she’s saying this because, like if you are in the water, you are still staying down on the ground, but once you are in the water you feel like you are losing gravity of yourself.
> Teacher: So being in water is like being in space? Why?
> Santiago: Like when you are in the swimming pool and like when you reach the bottom and then you can jump up high, from the bottom. That’s kind of like space.
> Teacher: Why is that like space?
> Santiago: Ah—you can jump high.

To understand this passage, in which Deena is able to draw a relevant and significant analogy, but is unaware of her own reasoning, saying “It’s like—I don’t know,” I turn to Karmiloff-Smith’s theory of representational redescription.

In *Beyond Modularity*, Karmiloff-Smith develops what she terms a "representational redescription" model of cognitive development. In this model, she identifies four levels of representational format. These are Implicit, and Explicit 1, 2 and 3. (I, E1, E2 and E3)

> At level I, representations are in the form of procedures for analyzing and responding to stimuli in the external environment… Information embedded in level-I representations is therefore not available to other operators in the cognitive system… A procedure *as a whole* is available as data to other operators; however, its *component parts* are not…
>
> The E1 representations are reduced descriptions that lose many of the details of the procedurally encoded information. As a nice example of what I have in mind here, consider the details of the grated image delivered to the perceptual system of a person who sees a zebra. A redescription of this into "striped animal" (either linguistic or image-like) has lost many of the perceptual details. I would add the that the redescription allows the *cognitive* system to understand the analogy between an actual zebra and the road sign for a zebra crossing (a European crosswalk with broad, regular, black and yellow stripes), although the zebra and the road sign deliver very different inputs to the *perceptual* system…
>
> The RR [representational redescription] model posits that only at levels beyond E1 are conscious access and verbal report possible. At level E2, it is hypothesized, representations are available to conscious access but not to verbal report (which is possible only at level E3)… we often draw diagrams of problems we cannot verbalize…
>
> At level E3, knowledge is recoded into a cross-system code. This common format is hypothesized to be close enough to natural language for easy translation into statable, communicable form.

These levels have been empirically verified. In one experiment described in *Beyond Modularity*, children were shown playrooms of a boy doll with a single toy car and a girl doll with three toy cars. The children were asked to which doll the experimenter was speaking if she said "Lend me the car" or "Lend me a car." By age 3, children have achieved behavioral mastery at this task, correctly assigning "the car" to the boy doll (who has one car) and "a car" to the girl doll (who has multiple cars). However, around age 5 and 6 these children start to make mistakes. Karmiloff-Smith argues that "representational redescription of each of these procedures into the more explicit E1 format makes it possible to link the common phonological form across the two representations of form-function pairs… In comprehension they start to make mistakes as to which of the two functions (numeral or indefinite reference ["one" or "one of"]) is intended." (p 57) That is to say, at the I-level students have a "black box" algorithm for arriving at an analogical map: they have a schema but aren't aware of that schema, are not aware of the instances from which that schema was derived, and are not able to pick apart how a new item (in this case outer space) is judged to be a member of that schema. Even more startling and provocative evidence for the implicit level comes from the reports of the children as to the reasoning they report for making their choice:

> the youngest subjects, even though they must have *used* the contrast between the articles to make their correct guess, explain this on the basis of real-world knowledge, saying something along the lines of 'You must have been talking to the boy, because boys like cars… Later in development, children explain their correct guesses by referring to the contextual features—for example, 'You were speaking to the boy, because he's got one car." It is really rather late in development, around age 8 or 9, that children make explicit reference to the *linguistic* clue that all children must have in fact used. (p 59)

When the teacher asks "Does anyone know why she said that?" she is, unwittingly perhaps, adopting the representational redescription model of students' levels of explicitness in their knowledge. Deena is able to draw a correct and relevant analogy, but is unaware of her own reasoning, saying "It's like— I don't know." Rebecca, in hearing the analogy, is able to abstract slightly—equating the feeling of being in water to "losing gravity." And Santiago relates this to space because in both places "you can jump high."

This raises an interesting question regarding my definition of analogy as a conscious choice—a deliberate reclassification of the object, subject to a new cognitive model (which may be interpreted as a distinct "form of procedures for analyzing and responding to stimuli in the external environment" (from Karmiloff-Smith, quoted above)). At what level of representational redescription are students able to make conscious decisions regarding their response to stimuli and deliberately reclassify objects?

Magnets as clay, magnets as electricity

The children in the above transcript are in the 5th grade—placing them at an age where Karmiloff-Smith observed linguistic abilities to be at the E2 and E3 levels. In the following transcript, I present data from a 2nd grade classroom. These students are between the ages 7 and 8 and, according to Karmiloff-Smith, less able to reason explicitly about concepts. Here this is evidenced by the confusion the students have using the analogies that they create. In this transcript, the students are discussing what's "inside" a magnet that makes it behave the way it does (lines 48 – 56).

> Renee: I think there is clay inside of it because clay does pick stuff—things, like paper and stuff.
> Teacher: Okay, so if there's clay inside here, does that help it stick to things? That helps the magnet stick? Ok, does it stick to paper, like clay does?
> Renee: Ummmm.
> Teacher: Okay, so the clay that's in here that you're saying is in here— what does it help the magnet stick to?
> Renee: Metal.

And later in the conversation (lines 92 – 97):

> Dalton: Because Evan said um well—I was thinking in my head when he said that there's magnets inside there—what are in

the other—what are in the magnets that are inside the big magnet?
Evan: Little pieces of metal.
Teacher: Little pieces of metal?
Dalton: Then what's inside *them*?
Student: Yeah- what's inside the little pieces of metal?
Taylor: Clay.
Teacher: Oh, Taylor has an answer, she says clay.

And following up on these comments (145 – 151):

Student: I am confused with Taylor.
Teacher: About what? Be specific what are you confused about.
Student: What she said before um Calvin was talking—
Teacher: You mean about the clay inside?
Student: Yes.
Teacher: Okay—do you want to add on to that?
Taylor: Um—I don't know what she's talking about.

There is something reasonable in Renee's statement—although neither she nor Taylor can articulate it and other students may not see it. There are a limited number of things that can stick to, say, your refrigerator and not fall down. Clay and magnets have crucial differences, of course, but more intriguing here is that Renee explains her reasoning that clay is inside magnets by stating: "clay picks stuff up." Is she thinking that there is, quite literally, standard modeling clay inside the magnet? Or is it more plausible that she is using clay as a prototypical member of the category of things that can "pick stuff up"—but do so in a way that does not fit with our standard p-prim of carrying? For while she uses the term linguistically in the first sense, if we recognize her knowledge to be at a less explicit level than language can effectively express, it is reasonable to believe that she "means" the second sense. Taking into account that languages often name categories after their prototypical or prevalent members (i.e. a Xerox machine for any copy machine), I contend that Renee is creating an analogy between the magnet and clay, assigning them to a category that she is terming “clay” because clay is an everyday object to a 2nd grade student. The students (including Renee and Taylor, proponents of the clay “theory”) do not recognize that clay is serving as the name of a category and not the thing itself and argue against the clay-theory by stating that “clay’s not that black” and suggesting perhaps the blackness is due to “food coloring” (again, “food coloring” may, to a young student, be a fairly standard way of changing the color of objects and so is used here as a way of signifying that color must be added—not necessarily food coloring).

When the base of an analogy (termed the vehicle in the context of metaphor) is used as both an exemplar and as an ad hoc name for a category, Glucksberg et al. (1997) all this linguistic move “dual reference.” As an example of dual reference,

> the phrase “a responsibility is a shackle” can be used to refer to the concrete, physical device that is made of metal, often has chains, can be locked around someone’s arms and legs, and so forth, and it can also be used to refer to the abstract, general category of constraining entities. We refer to such abstract, general concepts as attributive categories. (Glucksberg et al 1997 p 334)

The authors claim that “nouns can be used to make dual reference whenever a superordinate category has not been lexicalized and a category exemplar is available that is prototypical of that category.” What I hope to have demonstrated with the above data on “clay” is that this dual reference is an ability that young students have, but, consistent with findings from representational redescription do not have access to the “duality” of the reference: is a magnet a member of a superordinate category typified by clay or is it a member of a category of things that *are* clay?

The question of “being like” versus “being” is addressed in the same magnets conversation in a different context. While Renee has identified clay as an appropriate analogy because of the ability of both clay and magnets to pick things up, other students are curious about the ability of a magnet to exert a force *through* things and one suggests electricity as an analogy (lines 212 – 214).

Teacher: …He said this is a magnet, it's only a magnet, there's nothing in it except electricity.
Calvin: Electricity and the magnet.

After asked to explain, Dalton jumps in with a theory and the teacher summarizes his comments (lines 251 – 271):

Teacher: Okay, so to make this magnet work somebody hooked it up to a wire, pushed the on switch, stuff came down through the wire to the magnet?
Dalton: Electricity.
Teacher: Electricity did—and now the magnet works?
Dalton: Mmm hmm. It's kind of like that—it's magnetism.
Teacher: 'It's kind of like that'—you keep telling me that—'it's kind of like that.'
Dalton: Well it's not kind of like um—electricity. It's magnetism that flows down.
Teacher: Okay, do I have to plug this in to a wire?
Dalton: No—when you're making it.
Teacher: When I'm making it I have to plug it in. [Dalton: Yeah.] and give it magnetism. [Dalton: Yeah.] Okay. Who else has some thoughts on that process—Savannah?
Savannah: I have two thoughts on that.
Teacher: Okay—go ahead. Be nice.
Savannah: Make up your mind already! Between it kind of has something—
Dalton: That's hard to do! [Teacher: Okay.] It's hard to do both at the same time!
Teacher: Okay so Savannah what's your question. Specifically what's your question—what are you confused about—you're saying make up your mind Dalton. Between what and what?
Savannah: Kind of and it is. Or it isn't.

The students recognize that there is a fundamental difference between the magnet being electricity and it being like electricity, but Dalton is still unsure why he claims it might be electricity in the magnet. Were this an unreasonable assertion with no cognitive “meaning” in his statement, it would be indecipherable to a scientist. There is logic to his statement. Both are instances of the schema of action-at-a-distance—something rarely seen in daily activity (and not shared by clay—at least not on visual distance scales). And in this schema the property responsible for that action may have “electricity” as a prototype. (Dalton, after suggesting electricity, is asked what electricity is and relates an experience with being shocked.) In fact, in a true scientific description of the phenomena, electricity and magnetism are manifestations of the same electro-magnetic force, and any motion produced by a magnet is due to the electrical manifestation of that force. Dalton is onto something—but his grasp is at the E-1 level of representational redescription. In essence, when Dalton states “they used wires to put it [electricity] in. That’s why, um, some of them [the magnets] have little holes left from it—I’ve seen ’em,” or when Renee claims that she “went on this website about magnets and it said that there’s clay inside” they are doing the same thing as the child who explained why the experimenter must have been referring to the boy doll by saying: “You must have been talking to the boy, because boys like cars.” Because these students don’t have access to their own reasoning, they have to invent a plausible reason that is, in fact, less plausible than the actual reason that they must have had, but not had access to. This lack of access to one’s own reasoning echoes diSessa’s findings (also reported in an chapter 5) concerning a problem in which students are presented with bells made of the same material, same length, same height, but varying widths. Almost without exception students predict (erroneously) that the thicker bells will have a lower pitch. Though some have cognitive access to the schema they are using to predict this and can refer to particular instances from which this schema has been abstracted, not all do. DiSessa reports:

> Although most subjects were ready with analogies—church bells compared with jingle bells, xylophones, musical instruments of various sizes—I was struck that some initially could not produce any example of the phenomenon they identified to be at the root of the situation. This, along with the rapidity and expressed certainty of responses, heightened my confidence that a p-prim (or several) was at stake rather than analogy.

I think these youngest students have trouble separating the schema from the instance (that is clay from things-that-stick—a category typified by clay); but later (older students) have trouble putting them back together (as with bigger-means-lower and the xylophone).

Glossary

Analogy: The claim of likeness where it is not routinely or automatically conceived. Analogy includes similes and metaphors. I define analogy to entail the choice of an alternative cognitive model.

Category: Commonly considered “a group or set of things, people or actions that are classified together because of common characteristics.” Known not to possess rigorous propositional structure (i.e., they are not always grouped by common characteristics), it has been suggested (Lakoff, 1987) that the boundaries between categories are a result of cognitive models.

Cognitive model: “Can be viewed as ‘theories’ of some subject matter” (Lakoff, 1987). May be an ad hoc construction, a kind of “story” of how the world works in a particular situation. Our cognitive models define our categories (for example, it only makes sense to differentiate a bachelor from a non-bachelor when you have a cognitive model in which people reach a marriageable age and enter monogamous long-term relationships).

Metaphor: A figure of speech in which two things are compared, usually by saying one thing is another, or by substituting a more descriptive word for the more common or usual word that would be expected. Some examples of metaphors: the world's a stage, he was a lion in battle, drowning in debt, and a sea of troubles. As noted by Glucksberg and Keysar (1990) one may note similarity by saying that *copper is like tin*, but not the metaphorical construction *copper is tin*. Metaphor, then, is used as a comparison between two categorically related items when no commonly accepted name for the category exists (for example, *copper is metal*).

Phenomenological Primitive: “The intuitive equivalent of physics laws; they may explain other phenomena, but are not themselves explained with the knowledge system” (diSessa, 1993). Examples include “closer is stronger” (as an explanation for why it is hotter closer to a fire), “blocking” (as an explanation for why a car is stopped when it hits a wall), and “supporting” (as an explanation for why a book is held up by a table). These are basic stories that convey an elemental sense of mechanism.

Prototype: Defined operationally by Rosch, this is a category member that is easily learned, easily identified, can be used to generalize about the entire category, and comes to mind most quickly as a category exemplar. Barsalou points out that prototypes are a cognitive behavior and not cognitive structure. Lakoff points to the role of cognitive models as a possible cognitive mechanism for the prototype structure of categories.

Schema: Short “scripts” or stories that we have about the world and the way it works: *event schemas* that are abstracted from our experience of certain events, *image schemas* that provide structure for conceptualizations – “schemas of intermediate abstractions [between mental images in abstract propositions] that are readily imagined” (Palmer, 1996 p. 66) – and *proposition schemas*: abstractions that act as models of thought and behavior and specify “concepts and the relations which hold among them.” (Quinn, 1987)

Structure-mapping: “The central idea is that an analogy is a mapping of knowledge from one domain (the base) to another (the target) such that a system of relations that holds among the base objects also holds among the target objects. In interpreting an analogy, people seek to put the objects of the base in one-to-one correspondence with the objects of the target so as to obtain the maximal structural match… Thus, an analogy is a way of aligning and focusing on relational commonalities independently of the objects in which those relations are embedded.” (Gentner and Jeziorski, 1993)

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Curriculum Vitae

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Memberships:

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Fellowships:

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University Preparatory High School
- 10th grade Environmental Chemistry, 2002

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- Lead Teaching Assistant, Physics 121, 122, 123. 1998, 2000
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Workshops:

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- Analysis of Student Inquiry in Group Conversations About Physical Science at NSTA 2003.
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