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…
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> 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.
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> -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.
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> -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.