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,

> 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.

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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.

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, 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.

<u>*Networks*</u>

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

[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.

> 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)

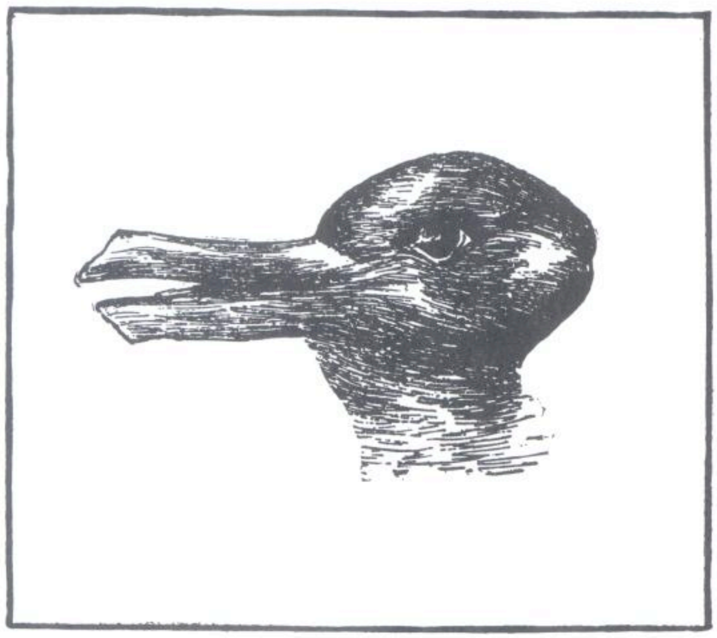
To understand the role that analogy plays for Kepler and "knowledge change" (p 28), Gentner (2002) argues that there are "at least six ways in which the process of analogical comparison can lead to knowledge change…

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.