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:

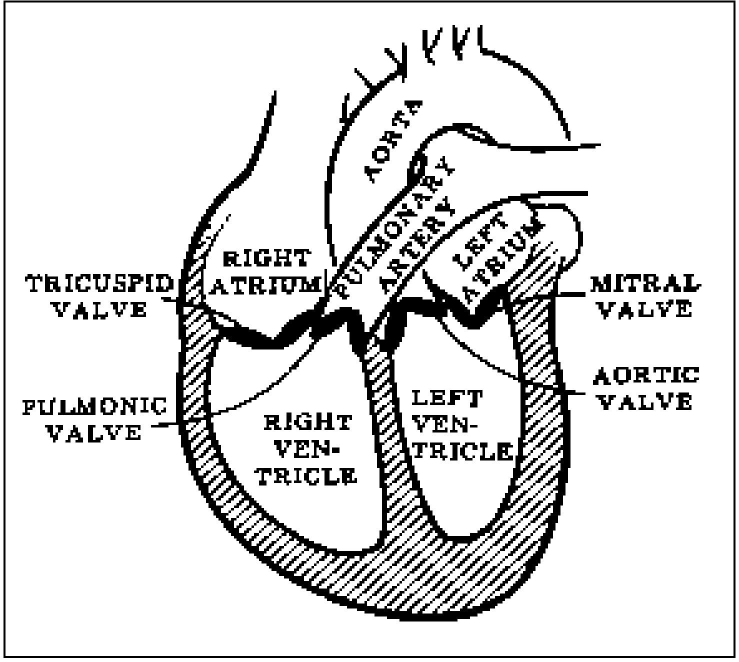

Fig. 7.1

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).

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: 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

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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.

- 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.