HANDS ACROSS THE DIVIDE: FINDING SPACES FOR STUDENT-CENTERED PEDAGOGY IN THE UNDERGRADUATE SCIENCE CLASSROOM

by

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ABSTRACT

This study explored college science students' and instructors' experiences with student-generated and performed analogies. The objectives of the study were to determine whether the use of student-generated analogies could provide students with opportunities to develop robust understanding of difficult science concepts, and to examine students' and instructors' perspectives on the utilization of these analogies.

To address my objectives, I carried out a case study at a university-college in British Columbia. I examined the use of analogies in undergraduate biology and chemistry courses. Working with three instructors, I explored the use of student-generated analogies in five courses. I carried out in-depth analyses for one biology case and one chemistry case. Data were collected using semi-structured interviews, classroom observations, researcher journal logs and students' responses to assessment questions.

My findings suggest that involvement in the analogy exercise was associated with gains in students' conceptual understanding. Lower-achieving students who participated in the analogy activity exhibited significant gains in understanding of the science concept, but were unable to transfer their knowledge to novel situations. Higher-achieving students who participated in the activity were better able to transfer their knowledge of the analogy-related science topic to novel situations.

This research revealed that students exhibited improved understanding when their analogies clearly represented important features of the target science concept. Students actively involved in the analogy activity exhibited gains in conceptual understanding. They perceived that embodied performatve aspects of the activity promoted engagement, which motivated their learning.
Participation in the analogy activity led to enhanced social interaction and a heightened sense of community within the classroom. The combination of social and performative elements provided motivational learning experiences valued by students and instructors. Instructors also valued the activity because of insights into students’ understanding that were revealed.

This research provides an example of how a student-centered, embodied learning approach can be brought into the undergraduate science classroom. This is valuable because, if instructors are to change from a transmission mode of instruction to more student-centered approaches, they must re-examine and re-construct their practices. An important step in this process is provision of evidence that change is warranted and fruitful.
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CHAPTER ONE
INTRODUCTION TO THE STUDY

The Problem

Despite the efforts of curriculum theorists and reformers during the last fifty years, college and university science education appears to remain largely unaffected by advances in curriculum theory and research. University instructors continue to use lecture-based strategies as their primary approach to teaching, and students continue to exhibit shallow, rather than deep understanding (Senk & Thompson, 2002) while demonstrating poor problem-solving skills (Ramsden, 1999).

The effect of these shortcomings is readily apparent to me; my experiences as a university-college instructor tell me that many of my students learn very little of significance during their years as undergraduates. Many of our courses are organized around memorization of facts to be recalled later on tests and exams, and students become adept at frantically copying down notes in lecture theatres, without much thought about what it all means. Students frequently lack the ability to apply their knowledge to more thought-provoking exam questions, while graduating students have problems applying their knowledge to new areas, and students entering the workplace carry with them few useful skills. A majority of my colleagues will agree with the observation that ninety-nine percent of what we teach our undergraduates appears to be forgotten shortly after they write exams (see e.g., Griffiths & Mayer-Smith, 2000).

As an instructor of chemistry and forensic science at a university-college, I have personally observed these problems in the science classroom, and I have, like so many other teachers, tried to analyze where the roots of the problems lie. Such analysis inevitably involves a degree of self-deception on the part of the instructor; it is always more comforting to concentrate
on our successes with the ‘good’ students than to consider our failures with the ‘poor’ students, and blaming poor academic results on the high schools or the work habits of students remains a facile and extremely tempting option. Finally, however, I came to the realization that there must be something fundamentally wrong with many of the processes used in the teaching of undergraduate science, and that what had worked well for me when I was an undergraduate might not provide the best learning environment for most students. It is this search for an alternate, and hopefully better, approach to science learning and teaching, that has brought me to this research topic, which centers on the use of analogies as heuristics in the science classroom.

For many years, I have used teacher-generated analogies in my classroom as a way of building bridges between the macroscopic, microscopic and symbolic worlds of science. However, although such teacher-generated analogies have improved student interest in the course content, many students continue to exhibit an inability to transfer knowledge from one aspect of science to another. As an alternate approach, I decided to involve students in modeling the function of a mass spectrometer, a complex scientific process which students often find conceptually difficult. During the modeling exercise the students became the molecules, the magnetic fields and the electric fields, and together became part of the machine and the chemical process itself. My students met this embodied approach with great enthusiasm, and I was eager to see whether their involvement in the exercise had led to a deeper understanding of the scientific processes and concepts involved. I was gratified to discover that, when asked about the mass spectrometer on the final exam, students exhibited understanding that I had not encountered before; they were remembering that molecules vibrated and rotated, something seldom recalled by my students in past classes. This observation provoked me to ask a question: can this type of multimodal approach, involving visual, actional, linguistic and performative communication,
lead to a more robust understanding of challenging science topics in the post-secondary science classroom?

Recent theoretical perspectives on the learning situation inform this question. Social constructionist perspectives on learning recognize that construction of knowledge in a classroom setting requires that the individual learner be an active participant in a process of interpretation within a social and cultural setting (see e.g. Duit & Treagust, 1995; Roth, 1995). My understanding of the social aspects of the learning situation is also enriched by Wenger’s (1998) description of the formation of sociocultural communities of practice. Members of communities of practice share goals and activities, but also have the ability to remodel the community of practice by their activities. From this perspective learning does not take place in isolation, rather it must involve a dialogic interaction with others, such as the teacher and other students. This requirement changes the role of the teacher from being the provider of deep understanding to a facilitator, or even co-author, of such understanding, and emphasizes the social nature of learning.

Understanding of the social aspects of learning is further informed by social-semiotic perspectives, which characterize communication as multi-modal and containing the interwoven features of speech, writing, image, gesture, facial expressions and models (Jewitt, Kress, Ogborn & Tsatsarelis, 2001). Fels and Meyer (1997) coupled the teaching of science with role-playing, and found that involving students in dramatization events was effective in enhancing social and community interactions, and in promoting understanding of science concepts for a group of pre-service elementary teachers who had limited background knowledge of science. Role-playing activities have also been used successfully to promote the learning of science for elementary and middle school pre-service teachers enrolled in an integrated college science course (Harwood, MaKinster, Cruz & Gabel, 2002). The work of Fels and Meyer (1997) and Harwood, MaKinster,
Cruz and Gabel hint at the value of bringing some type of multi-modal performative element into the post-secondary science classroom.

Taken together, the theoretical perspectives and empirical studies of socio-cultural and socio-semiotic aspects of learning suggest that teachers at all levels of education should make the shift from providers of information to designers, facilitators, and co-authors of understanding. Unfortunately, while arguments for attending to the social and dialogic aspects of learning clearly support embracing a “learning paradigm”, where students have a central and active role in their learning, the shift from the teacher-centered “instructional paradigm” has not been forthcoming in higher education (Barr & Tagg, 1995). Wood and Gentile (2003) note that the introduction of new instructional methods into university science classes has been slow and difficult, due to the lack of incentive to question or change traditional practices. Making the move from purveyors of knowledge to facilitators of student-centered learning is a big leap for the post-secondary science educator. Research on learning in elementary and secondary science classrooms has been used to argue for changing the culture and pedagogical practice in institutions of higher learning. But more examples of the value of adopting a learning paradigm in post-secondary science classrooms are needed. At present little is known about the merits of adopting multi-modal, performative teaching strategies to promote learning of the complex and abstract science concepts taught in university courses. It is the need to promote and enable the coalescence within the science classroom of these theoretically grounded factors - the social, the cultural, the dialogic, the linguistic and the multimodal - that forms the backdrop for this research, in which I study the relationships between the use of student-generated and performed analogies and learning within the undergraduate science classroom.
The Study

In the remainder of this chapter, I introduce my study and provide an overview of the purpose, research questions, research methods and significance of the study.

The Purpose of the Study

My purpose in conducting this study is to explore the use of student-generated analogies, within first year undergraduate science classes, as a way of providing students with opportunities to develop a more robust understanding of difficult science concepts. The analogies were developed and performed in the classroom by class members, with the assumption that this learning approach would promote and encourage meaningful embodied knowing.

A second purpose of this study is to examine students’ and instructors’ perspectives on the use of student-generated and performed analogies in the undergraduate science classroom. This was undertaken to determine whether instructors and students consider this approach pedagogically useful, and whether they recognize its value. As a college science instructor who has frequently used teacher-generated analogies in the classroom, I was also interested in recording my experiences and responses to student-generated and performed analogies.

Research Questions

With these purposes in mind, I asked the following research questions:

1. *In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?*

2. *What are the perspectives of college students and instructors on learning science using performed analogies?*
Research Methods

To explore my research questions, I conducted a naturalistic case study at Columbia University College (pseudonym), a four-year undergraduate institution in the lower mainland of British Columbia. The study was carried out from January 2003 to December 2004. The participants included faculty members, students in first-year science majors and non-science majors classes, and myself. One hundred and sixty-five students enrolled in eight undergraduate science classes and three instructors participated in the study. Twenty-seven of these students agreed to be interviewed after the analogy exercise.

The study involved an activity in which small groups of students developed, discussed and performed analogies relating to a conceptually difficult topic from the course curriculum. I first introduced the use of performed student-generated analogies in tutorial classes, and then individual students constructed their own concept-related analogies. Small groups of students then chose one analogy to represent the science topic, which they performed for their peers. The analogy performances were videotaped. On completion, the performances were discussed by the class and instructor.

I conducted semi-structured interviews to investigate the views of students and their instructors on the use of this type of analogy, and recorded their conversations on audiotape. I transcribed all interviews conducted with the study participants. I also attended and observed class sessions to gain a situated understanding of how learning was experienced and facilitated during the course. I documented classroom events through a personal journal. To assess students' understanding of the science topic I analyzed student test data and pre- and post-analogy probe questions. This data also allowed me to investigate links between the use of student-generated analogies and student conceptual understanding. In-class observations, interview data and journal entries were examined together to triangulate my findings.
Significance of the Study

This study, which explores students’ and teachers’ perspectives on the use of student-generated and performed analogies, and the relationships between use of these analogies and students’ conceptual understanding in the college classroom, can be viewed as significant from three perspectives.

- First, the findings of this study contribute to the understanding of educational practice by providing information on how the use of this type of analogy affects conceptual understanding. This is an area that has not been extensively investigated, and in which there is at present little information.

- Second, while the advantages of performance-related activities in encouraging students to take control of their own learning, and to develop a conceptual framework that is closely related to their own experiences, has been demonstrated in the arts (Brauer, 2002), there is little information on the possible benefits of these approaches in the undergraduate science classroom. This study, which provides science educators with information on how students and instructors view the use of student-generated and performed analogies, may encourage more use of these strategies in the college science classroom.

- Third, while many innovative approaches involving more student-centered classrooms have been shown to be beneficial at the high school level (Duit & Treagust, 1998), such approaches have not been widely adopted by post-secondary science instructors. The findings from this study can inform these science educators on how they can use student-generated performed analogies, and may encourage more use of these student-centered strategies in the post-secondary science classroom.
Organization of the Thesis

This thesis is organized into eight chapters. In chapter 1, I outline the problems, documented in the literature, that relate to the teaching and learning of post-secondary science, and discuss how educational theory can provide insights that illuminate many of these issues. I also describe how my study, by applying aspects of educational theory, could provide a novel approach for addressing some of these problems.

Having created a space for my study, I explain why I am interested in this area, and present the research questions I framed to explore and examine student and teachers' experiences and perspectives on the use of student-generated and performed analogies as a heuristic in the post-secondary science classroom. I then outline the research methods that I used in the study, and show how my study contributes to the body of knowledge relating to the use of analogies in the science classroom.

In chapters 2 and 3, I summarize and review the literature that informs this study. There are a number of areas of published work that illuminate, and provide support for, the research I have undertaken. Together, these provide the background for, and set the scene for, my study. Chapter 2 relates to what we know about how learning takes place in the undergraduate science classroom. I focus on innovative pedagogical approaches that have been, and are being, used within the undergraduate science classroom, and why these approaches have not been widely implemented. In chapter 3, I review the literature relating to the use of models and analogies. I clarify the meaning of the terms model and analogy, and discuss the distinctions and relationships between these. I then illustrate why models and analogies are viewed as powerful devices for understanding science. I also review the literature relating to the pedagogical use of analogies and models in the science classroom, and their utility for fostering conceptual understanding.
Chapter 4 of this thesis describes and justifies the naturalistic case study research methodology I employ in this study. I present the context of the study, including the university-college setting and the courses in which I conducted this research. I introduce the research study participants, both the teachers and students who volunteered to participate in the study. I then describe the data sources and the collection techniques that I used for the study, and explain the procedures I used to interpret and analyze my data. I conclude the chapter with a personal reflection on my own multi-faceted role as researcher, teacher, participant and colleague within this study.

In chapter 5, I use a series of short vignettes to take the reader through one cycle of performed analogies, showing how the various steps in the process are related. By presenting these from a personal perspective, I highlight the complexity of a process that is changed by the interactions of a number of participants. My reflections on this enactment are described as scenes in which I am, at different times, a director, a performer, a spectator and a critic. A dynamic flux exists between these roles, which in turn results in new insights into my roles.

In chapters 6 and 7, I present the results of my data analysis, and relate my findings to the research questions described in chapter 1. In chapter 6, I discuss the role of student-generated and performed analogies in promoting conceptual understanding for undergraduate science students. In chapter 7, I discuss students’ and instructors’ perspectives on the use of student-generated and performed analogies for learning science in the undergraduate classroom, and argue for the transformative potential of student-generated and performed analogies to enhance the learning experience within the undergraduate science classroom.

In chapter 8, I summarize the research study and the findings, present conclusions from the study, consider the implications of the study for teaching science in the post-secondary classroom, and make recommendations for further research.
CHAPTER TWO

REVIEW OF THE RELATED LITERATURE:

LEARNING IN THE UNDERGRADUATE SCIENCE CLASSROOM

Traditional teaching methods, centered on the primacy of the lecture, combined with passive learning in undergraduate science classes, can be counter-productive to meaningful learning while inhibiting students’ ability to apply knowledge (Barr & Tagg, 1995; Griffiths & Mayer-Smith, 2000; Ramsden, 1999). Mazur (1996) notes that lecturing can be problematic because students do not benefit from lectures that simply reproduce written material already available in texts or from notes that they can read beforehand, while critical thinking is often not required during lectures. Students schooled in this manner typically lack the ability to apply their knowledge to novel situations, and exhibit only surface learning rather than deep understanding (Senk & Thompson, 2002). These problems are widespread across institutions of higher learning, where traditional practice remains privileged, and despite the attention of many curriculum theorists and researchers, learning within the undergraduate science classroom remains largely unchanged and unquestioned. Innovative approaches that are more student-centered, such as those that foster group learning, have been shown to be useful (Bossert, 1988, 1989; Johnson & Johnson, 1989, 1993; Yuretich, Khan, Leckie & Clement, 2001). However, such approaches have not been widely embraced by undergraduate science instructors. This divide between curriculum theory and practice leads me to inquire more deeply into what we know about learning in the undergraduate science classroom.

To do this, I first examine the literature on learning theories that informs my study. My personal experiences in the college science classroom lead me to maintain a constructivist view
of learning, and the theoretical framework I adopt is based on constructivist perspectives. I next
describe innovative strategies that have been used in the undergraduate science classroom to
encourage the construction of conceptual understanding. I close by considering reasons why
these innovative teaching strategies have not been widely adopted by college science instructors.

Theoretical Perspectives on Learning

Constructivist perspectives consider learning to be an active, continuous process during
which learners construct personal meaning and interpretation based largely on their prior
knowledge and experience (Driver & Bell, 1986). Construction of personal meaning involves the
learner looking inward in order to organize and reorganize his or her own subjective past
experiences (Sumara & Davis, 1997). Thus, we cannot view learning as a transfer of knowledge
from teacher to learner, but as the learner actively constructing new knowledge based on prior
understanding (Duit & Treagust, 1998).

A rich body of research has led to the identification of a number of factors that can encourage what has been termed deep understanding\(^1\). Foremost stands the requirement for active involvement of individual students in the construction of their own knowledge, coupled with a shift away from teacher-driven lessons to student-centered learning. Constructivist perspectives on learning (Davis, Sumara & Luce-Kapler, 2000) support such a move. Also, as Bruner (1986) informs us, new knowledge must be meaningful to the learner if it is to be understood and remembered. When the learner can make connections between their existing

\(^1\) Deep understanding refers to the ability to reformulate knowledge in different ways, or to use knowledge in unfamiliar contexts (Leonard, 2002).
knowledge and new information, then the new information is more likely to be meaningful to them, and more likely to be retained.

Schön (1963) also considers the relationship between existing and new knowledge. In his model of concept development, he outlines how already accommodated theories and ideas can undergo modification, or displacement, when the learner applies prior knowledge to new and unfamiliar situations. Schön notes that this displacement is unpredictable, because the new concepts formed will depend on many factors. These include the prior knowledge that each individual holds, and how he or she uses and modifies this knowledge to interpret new information. This unpredictability in the construction of new understanding means that different learners can construct different conceptions based on the same information. Thus, from a constructivist perspective, the individual plays a decisive role in determining what is learnt. Learning is based on the connections that are made with what is already known, and what is known depends on previous experiences. Learning contexts can influence learning, and the meanings that an individual learner constructs may be modified by changes in context and situation.

Constructivism as a theory deals with how people learn, both individually and socially (see e.g. Duit & Treagust, 1998; Roth, 1995), but does not speak directly about teaching (Mayer-Smith & Mitchell, 1997; Davis & Sumara, 2002). Attention to constructivist perspectives, however, can indicate how the teaching environment can be tailored towards the encouragement of meaningful learning. If we accept the complexity of the learning situation, in which learners construct their own understandings in different ways, based on who they are, what they already know and on the dynamics of the situation, then learning cannot involve a mechanistic transfer of
a set body of knowledge from a teacher to the student. Instead, the role of the teacher becomes that of enabling the cognitive engagement of individuals in their own construction of knowledge (Prawat, 1989). In this situation, teaching is more aptly described as a matter of “... perturbation (trying to prompt new ways of sense making by interrupting established habits of interpretation) and construal (trying to make sense of the sense the learner is making in order to orient subsequent efforts at perturbation)” (Davis & Sumara, 2002, p. 3). Perturbation involves the teacher actively guiding the student towards new ways of understanding, while construal engages the teacher in constructing their own understanding of the learning process.

Establishing ways that teachers can fulfill this role is difficult, because there are probably as many teaching styles as there are teachers. However, it is possible to identify instructional approaches that enable the construction of knowledge. Instructional approaches can be characterized as being didactic, Socratic or dialogic (Gilbert & Boulter, 1998). Construction of knowledge by the student would be expected to require a dialogic approach, particularly if we expect perturbation to occur successfully. Dialogic instruction can occur in the post-secondary science classroom, but traditionally it is rare because the content-driven nature of much of the curriculum material, combined with the teacher-centered lecture format, makes implementation of such constructive dialogue difficult (Barr & Tagg, 1995).

Although some views of constructivism place the individual as the locus of cognition, during the learning process the individual is also responding and adapting to his or her social and cultural contexts, and learning is also influenced by these contexts. A focus on contexts and social interactions in learning is the theme of what has been termed social constructionism (Davis, Sumara & Luce-Kapler, 2000). Social constructionism has its roots in constructivist thinking, but the term social constructionism is often preferred over social constructivism by those who wish to distance themselves from the commonly held constructivist notion of an
isolated learner (Raskin, 2002). Framed in this way, construction of knowledge in a classroom setting requires that the individual learner be an active participant in a process of interpretation within a social and cultural setting (Roth, 1995). This focus on groups of learners, with their shared conversations and understandings, attends more to collective understanding and is less concerned with individual sense-making. In this context, students learn by interacting with each other, and in turn, this interaction can affect their desire to learn and their sense of identity within the group.

The benefits of group activity have been demonstrated by studies of students working together in co-operative learning environments (Bonwell & Eisen, 1991; Johnson, Johnson & Smith, 1991). When group activities take place in science classrooms, the development of learning communities is fostered, and feelings of isolation among students are reduced (Tobias, 1990, 1992). Participation in co-operative group discussions also encourages students to teach each other and to communicate both what they know and what they don’t know (Duch, 1996; Duncan & Dick, 2000; Gall & Gall 1993; Yu & Stokes, 1998). Collins, Brown and Newman (1989) and Khan (in press) found that students benefit from acting as both teachers and learners when interacting with other class members, while Lundberg (2003), in a study of college students, found that time spent in peer-teaching and discussion of science topics was the strongest predictor of understanding.

The success of these interactive learning environments is testimony to the claims of social constructionist researchers (see e.g. Lave & Wenger, 1991; Roth, 1995), who argue that deep construction of knowledge in the classroom setting takes place when the individual actively participates in a process of interpretation within a social and cultural setting. Because of the inseparability of the activity and situation from learning and cognition, both the nature of the learning activity and how the learner participates in that activity can significantly affect the
quality of the learning that ultimately results (Brown, Collins & Duguid, 1989). The social nature of learning has led some educators to speak about classroom environments as communities of practice (Wenger, 1998) where community members (students and teachers) shape their community through the activities in which they engage. Such views indicate that the teacher is extremely influential, as s/he ultimately decides which instructional strategies are most appropriate for students' needs, their prior knowledge, and the science content being introduced in these interactive settings (Grosslight, Unger, Jay & Smith, 1991). Teachers also assume an interactive role themselves, promoting conceptual learning through 'social negotiation' (Harrison & Treagust, 2000).

Social-semiotic perspectives characterizing communication as containing the interwoven features of speech, writing, image, gesture, facial expressions and models (Jewitt, Kress, Ogborn & Tsatsarelis, 2001) further inform our understanding of the social aspects of learning. From this perspective, learning is viewed as being dependent on how the learner interprets the complex multi-modal signs used by the teacher in communicating their own understanding. In a study involving seven high school science students, Jewitt, Kress, Ogborn and Tsatsarelis analyzed students' explanations relating to a laboratory exercise in which plant cells were observed under a microscope. Although the students were explaining the same exercise, their explanations exhibited a great deal of variation. The students' explanations were also multi-modal, involving speech, action (through experimentation), the use of analogies and images. Recognition of the importance of activities and situations as factors affecting learning led Fels and Meyer (1997) to couple the teaching of science with drama. Fels and Meyer found that performance-based pedagogical practice could be used effectively in elementary science education classrooms to enhance social and community interactions and promote understanding of science content. They noted that their pre-service elementary science education students "... brought forth their
knowing as language embodied in performance on the stage, and in doing so, embraced the monster that was once their science” (p. 80).

In conclusion, it is apparent that a rich body of research based on constructivist perspectives has led to the identification of factors that can encourage deep understanding. Foremost stands the importance of active involvement of individual students in the construction of their own knowledge, and a concomitant shift away from teacher-driven lessons to student-centered learning. Recognition and acceptance of this need has encouraged some undergraduate science educators to adopt innovative strategies that encourage a more student-centered learning environment. I will now consider how these student-centered approaches have been, and are being, used within the undergraduate science classroom.

**Innovative Strategies Used in the Undergraduate Science Classroom**

Innovative strategies that have been tried in post-secondary science classrooms include cooperative learning and related small-group activities, problem-based learning, thinking aloud pair problem solving, role-playing and the use of analogies. In the next section, I consider how instructors have used each of these strategies in the post-secondary classroom, and discuss the benefits and disadvantages associated with their use. Although these strategies have often been examined in isolation, it is important to note that in the complex world of the classroom these strategies are oftentimes melded together, so that it becomes challenging to study them as individual and rigidly defined entities.

**Cooperative Learning and Structured Small-Group Activities**

Structured small-group activities have long been used in elementary and high school classrooms, but have not been as widely used in undergraduate science classrooms (Johnson,
Johnson & Smith, 1991). However, the perceived need to engage college science students in more active learning has, in recent years, led to the introduction of structured small group activities, in which students work with their peers on defined tasks (see e.g. Coppola, 1996).

Simply assigning students to groups to learn does not necessarily promote higher achievement (Johnson, Johnson & Smith, 1991). A crucial requirement identified by these researchers is that group activities should be cooperative in nature. To be cooperative, a learning group must exhibit ‘positive interdependence’, where each member contributes to, and gains from, the understanding of other group members. Individual members must also be ‘accountable’ for their share of the task, and must have good ‘interpersonal and small-group skills’. When these requirements are met, ‘face-to-face promotive interactions’ within the group can take place, leading to enhanced learning (Leonard, 2002).

The advantages associated with cooperative learning are particularly valuable in the science classroom, where educators are troubled by failing to engage and retain science students. In a meta-analysis of small-group learning in science, math and engineering undergraduate courses, Springer, Stanne and Donovan (1999) found that students’ involvement in cooperative learning situations promoted greater academic achievement, and improved student retention and attitudes towards learning. Johnson and Johnson (1989, 1993), in a meta-analysis of over 1200 studies, have also demonstrated the pedagogic value of cooperative learning. Their results indicate that students who engage in cooperative learning retain more knowledge, become more articulate, develop better social skills, respect differing viewpoints and enjoy their learning experience more than students taught by traditional methods, which were typically centered on lecturing.

Yuretich, Khan, Leckie and Clement (2001) have studied the incorporation of small-group cooperative learning strategies into large university lecture classes. Large lecture classes
for oceanography students were modified to include cooperative small-group learning through interactive in-class exercises and directed discussion. Under these conditions, student achievement showed significant improvement, while a majority of students commented on surveys and during interviews that they had increased interest in science.

Cooperative small-group activities have been combined with other strategies to provide mentoring for students (Khan, in press). In a study of female college chemistry students, three classroom strategies were used to mentor students. These were “career pathways”, in which the instructor described the pathway she followed to a science career; “internships”, for which students were provided with information on possible placements from former students and a web site, and “structured heterogeneous cooperative groups”, consisting of small groups of students who were organized to work cooperatively on assigned coursework. Results from student survey responses indicated that students believed that their learning was enhanced through involvement in small-group cooperative learning. Survey results also suggested that involvement in this mentoring exercise may also have encouraged these female students to stay in science.

While there are well-recognized benefits of cooperative learning (Smith, 1993), a number of factors can negatively affect implementation in the science classroom. All participants in the post-secondary learning/teaching process - teachers, students and administration - are affected by the existence of the teaching paradigm (Barr & Tagg, 1995), which values maintenance of teacher-centered pedagogy over a more student-centered learning paradigm. Thus, failure to implement cooperative learning approaches successfully may result from a confluence of many factors related to the experiences and beliefs of faculty, students and administration (Herreid, 1998). For example, inadequate training of instructors (Johnson & Johnson, 1989, 1993), who may have little or no experience of using student-centered classroom activities, can act against successful implementation. The prior experiences of students are also important. Herreid (1998)
notes that it takes time for students to learn to work together as a team and, even under the best of circumstances, some groups will have difficulty working cooperatively.

**Peer Teaching Using Thinking Aloud Pair Problem-Solving (TAPPS)**

To support cooperative learning situations, in which students learn from each other, it is necessary to redefine and realign the roles of teachers and students (Lundberg, 2003). One pedagogic approach, which promotes this realignment, is the use of Thinking Aloud Pair Problem-Solving ('TAPPS') (Pestel, 1993). In this classroom strategy, students form pairs in which one person is the problem solver and the other person is both the listener and the questioner. Instructors and students then participate in an in-class discussion relating to the method and explanations used. Pestel (1993) describes TAPPS for use in chemistry problem solving, and Griffiths and Mayer-Smith (2000) have used TAPPS for genetics problem solving.

The use of TAPPS has a number of benefits. For example, Breslow (2001) found that students became aware of the processes they were using, and were able to reflect on problem solving strategies. Pestel (1993) found that students using TAPPS actively engaged with the problem and, by articulating and questioning the approaches they were using, developed and refined problem-solving skills. Students were then able to apply these new skills, instead of relying on memorized templates for rote solutions to problems. Pate, Wardlow and Johnson (2004) demonstrated that students involved in TAPPS were more successful at solving technical troubleshooting problems, and viewed TAPPS as an important step in the development of metacognitive skills relating to the technical problems. Strategies that encourage students to learn from each other support the notion that students themselves may be the most valuable resource for helping other students to engage in learning (Lundberg, 2003). Through their efforts to introduce TAPPS in an upper-level genetic analysis course, Griffiths and Mayer-Smith (2000)
learned, however, that adopting thinking aloud pair problem-solving can be challenging for students and teachers. They point out that most students have little experience in verbalizing their knowledge, and are more comfortable listening and memorizing information, and teachers may need to be convinced that TAPPS is a valid and useful method.

**Problem-Based Learning (PBL)**

Problem-based learning (PBL) is another strategy that promotes a student-centered classroom through structured group activities. PBL makes use of real life situations or vignettes as a starting point to help students contextualize a problem that they will work on. Students typically work in groups of five to seven on an assigned problem, and while learning is self-directed, a tutor is typically available to provide assistance. Duch (1996) observed that students in her honors general physics course learned to teach each other by communicating both what they knew and what they did not know, in order to solve complex real-world problems successfully. She found that this form of group problem-solving demonstrates to students that there are many ways to solve a problem, while challenging them and motivating them to learn. Involvement with PBL was also motivational for Duch, who discovered that the excitement and energy created when students work together in groups, where they challenge, question and teach each other, made her involvement in problem-based learning particularly worthwhile. Other benefits cited for PBL are that students learn to integrate knowledge from different areas (Kjellgren, Ahlner, Dahlgren & Haglund, 1993), and are more likely to retain what they learned and apply their knowledge appropriately (Albanase & Mitchell, 1993).

In common with other forms of student-centered learning, successful implementation of PBL requires that the role of the instructor must change from transmitter of information to facilitator of learning (Kjellgren, et al. 1993). This shift in role may be problematic. In a study of
the perspectives of seven instructors' who taught a PBL undergraduate environmental science education course, Dahlgren, Castensson and Dahlgren (1998) found that the instructors expressed different conceptions of PBL, based on whether they viewed pedagogy from a teaching or a learning perspective. The instructors also held two different views concerning their role as a tutor in PBL, which Dahlgren, Castensson and Dahlgren categorized as either directive or supportive. The directive instructors viewed their role as providing instructions and answers for the students, while the supportive instructors viewed their role as a resource for students. The supportive instructors emphasized student involvement and responsibilities in group activities. The researchers found that instructors who had a teaching perspective on pedagogy viewed PBL from a directive perspective, and were uncertain about their role in PBL. Teachers with a learning perspective held a supportive view of PBL, and saw their role of tutor as being supportive of the students' needs. Thus, the message seems to be that implementation of student-centered strategies, such as PBL, may be impacted negatively if instructors’ views on pedagogy do not support a student-centered classroom.

**Role-playing and Drama**

A common feature of cooperative learning situations is that the learner is actively and socially engaged in generating understanding (Slavin, 1983). These features, which promote student interest and community, are also present when the learning activity involves role-playing and drama. Although the use of role-playing is common in grade schools and within the arts, there are very few examples of the utilization of role-playing activities in a post-secondary science setting. Harwood, Makinster, Cruz and Gabel (2002) describe one study where role-playing has been used successfully in learning science. In a college-level integrated science course for elementary pre-service teachers, individual students adopted roles for a senate hearing.
centered on global climate change. Students’ knowledge and attitudes were evaluated by the use of four open-ended questions, and by specific questions relating to global warming on a final exam. The authors conclude that role-play experiences were both powerful and memorable, facilitating students’ learning of scientific topics while fostering pre-service science teacher development by serving as an example of a successful teaching strategy. Benefits of dramatization have also been demonstrated by Palmer (2000), who used student-directed dramatizations of science concepts with a group of third year undergraduates who were training to become preschool teachers. The author asked students to invent and perform a dramatization to illustrate a science concept that the instructor had described. After the dramatization, Palmer asked the students to evaluate the strategy. Analysis of the student comments indicated that dramatization helped the students to learn science by making the concepts more visual and memorable, while increasing students’ interest and motivation for the subject. He suggests that this strategy may help future elementary teachers, who tend to avoid teaching science (Kyle, Bonnstetter & Gadsden, 1988), become more adept at teaching science-based topics.

The use of dramatization to help students increase their comfort level in a problematic area is also illustrated by Deeny, Johnson, Boore, Leyden and McCaughan (2001), who used drama and group discussion to help first year nursing students to find ways of dealing with death and dying. The students first performed two ten minute dramas dealing with issues and feelings relating to death and dying. In-class group discussions then took place. To determine the effectiveness of this approach, the researchers asked the students to complete a questionnaire one week later. The authors note that the students not only readily accepted this strategy, but also that it increased students’ interest and involvement in the topic, while helping them to see connections between abstract ideas and concrete phenomena. Students learned from participating, experiencing, reflecting, describing, talking about and analyzing what they had
seen and done. Deeny, Johnson, Boore, Leyden and McCaughan consider the combination of drama and group work to be an effective learning strategy that could be added to a repertoire of teaching methods to improve communication skills, coping strategies and human skills such as empathy and understanding.

**Learning With Analogies**

One approach to enhancing conceptual understanding which has been widely used in the post-secondary classroom, and which has been shown to encourage the construction of new understanding from prior knowledge, involves the use of analogical models. Science makes use of analogies in many ways, but the essence of analogy use is always that new knowledge is constructed by reference to something already understood (Duit, 1991). Research in post-secondary classrooms has indicated that the development and use of analogical models can play an important role in promoting deep understanding of science concepts. For example, Clement (1989) notes similarities between the creative analogies produced by beginning undergraduate science students and those produced by expert scientists (Clement, 1981). In his study, student analogies were found to be indicative of conceptual change, and to involve re-evaluation and refinement of the students’ prior understanding.

Analogical learning is most successful if students have an intimate understanding of the analogical model. Such an environment is provided when students devise their own analogies. Indeed, the limited research published on the use of student-generated analogies indicates that involvement of students in developing their own analogical models can play a particularly important role in promoting conceptual understanding (Harrison & Treagust, 2000; Wong, 1993). Wong concluded that self-generated analogies led to student teachers extending their knowledge by devising new explanations and raising questions relating to the phenomena being
studied. Wong also found that student-developed analogies can encourage ownership of the material being studied, because students' personal analogies are often more familiar and more applied than those developed by the teacher.

It is apparent that the use of analogies in the classroom offers rich possibilities for promoting conceptual understanding for diverse groups of students (Clement, 1993; Harrison & Treagust, 2000; Wong, 1993). Because of this potential, coupled with the central role of student-generated analogies within my research, I present an in-depth discussion of the role of analogies in science education in chapter 3.

**Reasons Why Innovative Teaching Strategies are not Widely Adopted**

While arguments for attending to the social and dialogic aspects of learning clearly support embracing a "learning paradigm", where students have a central and active role in their learning, the shift from the teacher-centered "instructional paradigm" has not been forthcoming in higher education (Barr & Tagg, 1995). Tobias (1992) notes that, while 300 studies on reforming undergraduate science education had been published in the previous decade, this body of research has had limited effect on science teaching in colleges. This leads us to wonder why reform strategies have not been widely adopted.

Research on learning in elementary and secondary science classrooms (see e.g., Duit & Treagust, 1998) has been used to argue that attempts to introduce novel teaching strategies must be accompanied by changes in culture and pedagogical practice in institutions of higher learning. Barr and Tagg (1995) suggest that the failure to implement innovative approaches in the post-secondary classroom results from their piecemeal insertion within a dominant ‘Instruction Paradigm’ that causes the innovation to be rejected or distorted. In exploring the slow progress of
change in post-secondary classrooms, Sunal, Wright and Sunal (2005) identified barriers that inhibit a shift in practice. These include:

- The culture at large inhibiting change in teaching
- The preservationist role adopted by many curriculum committees, which tends to support the status quo
- A lack of pedagogical background for science instructors, and of professional development for instructors
- Budget and resource issues that arise because introducing innovations is expensive in terms of faculty time, teaching space and resources
- The structure of the institution affecting instructors’ practice by, for example, giving few rewards for teaching excellence
- The perceived realities of the classroom, such as large class size, influencing teachers to make only minor changes.

Fullan (2001) proposes that implementation of change is a highly complex and subtle social process. He notes that key factors that affect the success of instructional change are (a) need, (b) clarity, (c) quality and (d) practicality of the change. Successful implementation of change at the classroom level also requires the consideration of elements such as the use of new or revised materials, the use of new teaching approaches and alteration of beliefs (Fullan, 2001).

A number of these elements that inhibit change are pertinent to my research because the introduction of student-generated and performed analogies into the college science classroom can only be successful in an environment that is conducive to change. I will discuss these factors and barriers from the perspectives on change given by Barr and Tagg (1995) and by Fullan (2001). We should, however, remember that these variables cannot realistically be considered in isolation, because they interact and affect each other.
While schoolteachers must proceed through a defined training program, college science faculty members typically have little or no professional training that prepares them for teaching at the post-secondary level (Sunal et al, 2001). Many instructors simply reproduce the teaching methods and ideology that were successful from their perspective, assuming that if it worked for them, it should work for their students (Sunal et al. 2001). This attitude automatically favors the status quo, and inhibits change, while providing a learning environment unsuited to the needs of many students.

Instructors can be seen as the interface between curriculum and students. Thus, the success or failure of any curriculum change rests in the hands of instructors; and, as noted by Hofstein and Walberg, (1995) “... the best curriculum materials can result in limited student growth if a teacher is insensitive to the intended goals, to student needs, and to appropriate teaching strategies” (p. 74). One of the reasons for this insensitivity is that many university instructors are unaware of modern theories of learning, or that there are pedagogically meaningful alternatives to lecturing (Sunal et al., 2001).

Even when instructors are aware of alternative teaching strategies, these strategies may not be adopted (Sunal et al., 2001); faculty who viewed their role as either disseminator of the discipline, lecturer, or information provider were less likely to implement significant change in their courses than faculty who described their role as a facilitator of learning. The authors conclude that for effective change to take place faculty must experience dissatisfaction with their existing ideas of science teaching, followed by cognitive conflict relating to their conceptions of teaching. Faculty must also realize that innovative pedagogical strategies for instructional change are plausible (Posner, Strike, Hewson, & Gertzog, 1982).

While such changes must occur at the individual level, they must also be, at least to some extent, institutional. Consideration of complexity theory has led to the conclusion that change
produced by fiat can never solve complex problems (Senge, et al., 2000). Thus, a change in learning orientation is required, and this involves everyone in the system: “Anything else is tinkering” (Fullan, 2001, p.103). Unfortunately, one important group of participants – students - are typically powerless and have no input on the change process. This is perhaps not surprising; Fullan (2001) notes that “People think of students as the potential beneficiaries of change. They rarely think of students as participating in change” (p. 13). I posit that it is important to remember that while each educational setting is unique and inherently complex, with ever-changing variables and inputs, the needs of our students are one factor that remains, yet is often unconsidered in attempts at curriculum change.

To sum up, the reasons for the failure to implement pedagogic changes are numerous and complex. Some, such as the existence of a teaching rather than a learning paradigm and time restrictions, are system-wide, and affect most institutions. Others, such as the beliefs and background of individual instructors and students, can also lead to failure of innovative change. These challenges are daunting, but must be addressed if we wish to bring change to post-secondary classrooms.

Earlier in this chapter, I described my recognition of the need for more student-centered approaches to learning. Fullan’s (2000) other requirements of clarity, quality and practicality can be fulfilled by most of the pedagogical strategies described earlier, but it is apparent that these approaches are foreign to most science instructors in post-secondary institutions, and thus have not been widely accepted or adopted in science teaching. I believe that one way to address Fullan’s requirements can be by the use of analogical models, which have an established place in the learning of science and are associated with deep understanding of science concepts (Harrison & Treagust, 2000). Because of their use in scientific endeavor, analogies are more likely to be accepted by science instructors and students than other innovative pedagogical practices. This
led me to investigate the use of student-generated and performed analogies as a way of promoting deeper learning in the undergraduate science classroom. In the next chapter, I more fully define analogies, and detail what we know about their pedagogical uses in the science classroom.
CHAPTER THREE
REVIEW OF THE LITERATURE RELATED TO
ANALOGICAL LEARNING

As mentioned previously, there are a number of pedagogic approaches that have been shown to be promising for promoting deep understanding, yet these have not been widely incorporated into the undergraduate science classroom. Of these approaches, the use of analogies already has an established place in science, where they fulfill a multitude of roles, including aiding in the understanding of unfamiliar concepts by allowing comparison with objects or ideas that are more familiar to the learner. This ability to aid in conceptual understanding is of particular importance within the undergraduate science classroom.

In this chapter, I define what the terms analogy, analogical model and analogical learning mean. I then describe why analogies are viewed as powerful devices, which can aid in the understanding of science, and how they have been used in the undergraduate science classroom. I will then consider why, despite their ubiquity and demonstrated usefulness, analogies have not been widely used to encourage deep conceptual understanding in the undergraduate science classroom. Because my research interests are the pedagogy of undergraduate science classes for science majors and non-science majors students, I concentrate my discussion on what we know about the use of analogies for this subset of learners. However, as relatively few studies on these specific areas are reported in the literature, I will draw on examples at high school as well as undergraduate levels.

The Meaning of the Term Analogy

While analogies have many uses in science, the essence of analogy is always that new
knowledge is assimilated and interpreted by reference to something already understood (Duit, 1991). The already-understood artifact can be mental or physical, and is referred to as the analogical ‘model’, while the new artifact is referred to as the analogical ‘target’. Analogical models can be objects, systems, or processes “... designed to reproduce as faithfully as possible in some new medium the structure or web of relations in an original” (Black, 1962, p. 222). These models render aspects of the target system that may be complex or abstract, or on a microscopic or macroscopic scale, easier to visualize or understand (Gilbert & Boulter, 1998). Often, analogical models are used to produce a simpler representation of a phenomenon. For example, Bohr’s model of the atom is a simple model of a complex structure. Models can, however, also add complexity to the phenomenon under consideration. For example, the use of kinetic molecular theory to explain the expansion of gases when heated at constant pressure involves using a complex model to represent a seemingly simple phenomenon.

Analogies can facilitate new understanding through a process known as analogical learning. In order to relate the use of analogies to this learning process, I draw upon the perspectives provided by Schón (1963), who noted the importance of shared relations that emerge from the process of using analogies, and that the term analogy can also be applied to a relationship signified by a process of thought. This view is supported by Duit (1991) who uses the term analogy to define “a relation between parts of the structure of two domains” (p. 666); Duit views analogy as a powerful tool enabling the comparison of similarities between structures. These perspectives indicate that analogies are better described as ‘analogical relationships’, where the relationship is between the analogical model and the target. This view is supported by Gentner and Markman (1997), who note that “Common relations are essential to analogy; common objects are not” (p. 48). They emphasize that the relationships between the analogical model and target are more important than their physical similarities.
The distinction between analogical relationships and physical similarities of a model and target is also important when analogies are used in the classroom. Grosslight, Unger, Jay and Smith (1991) indicate that many students, whom they classify as Level 1 (i.e. novice) modelers, consider analogical models to be exact copies of the target. A teacher may present to these students a model with either implicit or explicit reference to analogical relationships between model and target, but students with undeveloped modeling skills will not perceive a model or an analogical relationship. They will perceive an uninterpreted metaphor, such as ‘the electron is a cloud’, along with all the confusion of meaning and intent inherent in a metaphor, which is full of implicit possibilities but which will remain unrecognized and unhelpful if the process of interpretation of the metaphor has not taken place. It is apparent that analogical learning requires the recognition of analogical relationships between the model and target. In order to examine how the learner constructs these relationships, it is useful to consider theoretical perspectives on learning with analogies.

**Theoretical Perspectives on Learning With Analogies**

To understand how analogical models and analogical relationships can promote deep understanding, it is important to position the use of these learning tools within a theoretical framework. While considering the perspectives of a number of theoreticians, I will maintain a constructivist perspective on learning. According to constructivist perspectives on learning, effective learning occurs when the learner constructs new meaning based on prior knowledge and experience (Driver & Bell, 1986). This construction of knowledge involves the creation or revelation of connections between prior knowledge and new information (Bruner, 1986). These connections can be made through the use of analogies, because the essence of analogy is that new knowledge is constructed by reference to something already understood (Duit, 1991).
Constructivists claim that an individual’s understanding of scientific concepts is dependent on interpretation of their prior ‘experiences’. These prior experiences include the introduction to, and interpretation of, models, and the significant role of models in the construction of scientific conceptions is well recognized. The concept of ‘experiences’ can also be interpreted to include the social interactions that take place within a learning situation, and which are inseparable from the use of models and analogies. These social interactions may involve other students and/or teachers. Of particular importance are the interactions with the teacher, who can help to reveal the “conventions of interpretation” (Black, 1962, p. 220) that must be used to interpret an analogical model, so that the presence of positive, negative and neutral analogical relationships can be illuminated, and student alternate conceptions detected and revealed. These requirements are consistent with a cognitive perspective on learning in which the student “... needs to form mental models of a phenomenon and to share these with others in the form of expressed models” (Gilbert & Boulter, 1998, p. 60).

The identification of analogical relationships requires comparison between the model and target. However, comparison alone will not lead to deep understanding of the target. Schön (1963) suggests that “Comparison by itself never produces anything significantly new” (p.25). In making this statement, Schön is not denying the usefulness of comparison as a method of filling in the missing details, in the way that simple models and analogies can be used in the classroom. The important emphasis here is on ‘by itself’. In order to synthesize new and insightful understanding, comparison needs to be the starting point from which new understanding and perceptions can grow, through a process Schön describes as ‘displacement of concepts’. The important feature of Schön’s displacement of concepts is that already accommodated (old) theories, ideas and understanding can undergo displacement when applied to unfamiliar (new) situations. Displacement involves change in the concept because of the application to the new
situation. Schön notes that this displacement cannot be predetermined, and can produce many new concepts. Analogical transfer is a process by which we view the new as the old, and in which there are many possible analogical relationships. Schön’s mechanism for the displacement of concepts is indeed through such analogical relationships. The only difference is in nomenclature – Schön’s ‘old concepts’ become the analog/model, while the ‘new concepts’ are the target. These parallels lead Schön to note, “Observation of analogies is the result and partial justification of the displacement of concepts” (p. 41). My concern is that, in making this statement, Schön may have cause and effect reversed – I believe that the displacement of concepts can only take place through the process of deriving analogical relationships, so that displacement of concepts is the result of the discovery of analogical relationships.

Semantics apart, it is apparent that analogy and models are placed centrally within Schön’s displacement of concepts. When he then proposes that learning involves “... emergence of new behavior built on the projective model of the old” (p. 108), he has completed a constructivist linkage from model/analogy to displacement of concepts to learning. This is compelling because of the many situations that can be viewed in this way. From a constructivist perspective, the student using Bohr’s planetary model of the atom can be considered to be participating in a lifelong and continuing displacement of concepts, from infancy onwards. Thus, the infant’s concept of falling will, for the student in elementary school, change to include an understanding of gravitational attraction for earth-bound objects. For the high-school student this understanding will then change to accommodate an understanding of gravitational attraction between objects in the solar system, and for the undergraduate will finally change to include understanding of interactions between sub-atomic particles. During this process, each old concept is changed or displaced, and the links between the old and new concepts involve the construction of analogical relationships.
The nature of the process whereby analogical relationships are constructed is addressed by Gentner (1983), who argues that a structure-mapping engine (SME) is involved in the interpretation of analogies. Gentner’s psychological interpretation is thought-provoking, but rather mechanistic. She argues that the SME involves three stages of analogy mapping. In the first stage, all identical properties are mapped in a process that will include lower-level, object-based similarities and higher-level relational structures. In the second stage of mapping, these matches are combined into “structurally consistent connected clusters (called kernals)” (Gentner & Markman, 1997, p. 50). Gentner and Markman argue that in this structure-mapping process, deeper relational interpretations are intrinsically more appealing to the learner, and will be favored over lower-level object-based interpretations. A third stage involves a merging of these kernals to give a small number of structurally consistent interpretations of the analogy. The SME then allows evaluation of the interpretations in an iterative process. Each individual learner will follow an idiosyncratic mapping process, with the result that many different interpretations of an analogy can be constructed. This renders the use of analogies in the science classroom complex. There are, however, certain factors that are known to be important in enabling analogies to be used successfully in the science classroom. These factors are addressed in the next section, in which I describe examples of analogy use within the science classroom.

**The Use of Analogies in the Science Classroom**

Analogical models are used routinely, and often unconsciously, by experienced scientists, teachers and students, and the use of analogies and models has, for many years, been important at all levels of science instruction (Gilbert & Boulter, 1998). There is evidence that analogies are powerful tools for promoting understanding of science (Clement, 1989; Coll & Taylor, 2005; Duit, 1991; Treagust, Harrison & Venville, 1998). Duit posits that analogies are valuable
because they can promote conceptual change learning, while providing visualization of abstract concepts and increasing students' interest and motivation to learn. Duit also notes that the use of analogies may reveal students’ alternate conceptions and encourage teachers to consider students’ prior knowledge. To illustrate ways in which the use of analogies in the science classroom promotes understanding of science concepts, I next describe examples of the use of analogies in science classrooms, and identify important pedagogical features.

If the application of analogies in the classroom is to be fruitful, it is important to consider whether their use encourages analogical learning for a wide range of students with differing backgrounds and abilities. There is evidence that analogies can be useful for students of different achievement levels. A number of studies indicate that lower-achieving students benefit most from the use of analogies, while higher-achieving students do not experience marked benefits (Gabel & Sherwood, 1980). Duit (1991) suggests that higher-achieving students may not benefit from using analogies if the target phenomenon is not sufficiently challenging; if a student already has a firm conceptual understanding, then the use of an analogy may be unnecessary, and only the lower-achieving students may gain from the use of the analogy. In contrast to the findings of Gabel and Sherwood, Sutala and Krajcik (1988) observed that students of all cognitive abilities benefited from using analogies. Students with low cognitive abilities profited most when the teacher helped them to make analogical connections, while students with higher cognitive abilities gained most from developing their own analogical relationships.

For analogical learning to take place, students must have well-developed modeling skills that enable them to map the important relationships between the analogical model and the target (Gentner & Markman, 1997; Harrison & Treagust, 2000). Grosslight Unger, Jay, and Smith (1991) suggest that teachers can enhance students’ modeling skills if they sequence their use of models, so that the learners are progressively challenged by encountering more demanding types
of models. Multiple analogical models have been used by Kurtz, Miao and Gentner (2001), in a process they describe as “mutual alignment” (p. 419). Students were simultaneously presented with two related analogical situations. Comparison between the two related analogies led to the students noticing structural parallels, which produced deeper understanding of the two situations.

Students may fail to carry out analogical mapping between the model and target when the relational jump from the initial analogical model to target is too great to allow construction of the intended analogical relationship. Clement (1993) investigated students’ understanding of analogies relating to the belief that a static object cannot exert force on another object, an alternate conception commonly held by physics students. In Clement’s study, 112 high school physics students were tested on their understanding of two analogically-related situations. While 96% of the students correctly believed that a spring pushes up on a hand when the hand is pushing down on the spring (case A), 76% of the students incorrectly believed that a table does not exert an upward force on a book that is placed on it (case C). The two situations are linked analogically, but students were unable to map the relationship between them. Clement used a structured sequence of related bridging analogies, which gave students a qualitative and intuitive understanding by dividing the analogical relationship into two small steps rather than one large step. This was done by introducing the intermediate (‘bridging’) situation of a book resting on a flexible board (case B). While students could not map the relationship between case A and case C, they were able to intuitively accept the validity of relationships between case A and case B, and between case B and case C. Thus they were also persuaded that case A was analogous to case C. Clement proposed that the use of the bridging analogy was successful in promoting analogical reasoning because of three factors. Students, who had good understanding of the analogical model B, were able to confirm that the analogical relationship between case B and case C was plausible, and were able to apply the sequence of analogical relationships A to B and
B to C. Clement notes that the intervention, which involved problem-solving, demonstrations, small-group lab activities and large-group discussions, could be considered an example of "guided constructivism" (p. 1254). Clement's work and other studies (see e.g. Gentner, 1983; Zook, 1991) indicate the importance of teacher guidance and scaffolding as a means of encouraging learning, and more specifically in enabling students to map and understand analogical relationships.

Students' ability to map relationships between an analogical model and target is influenced by the existence of prior alternate conceptions. Prior conceptions have been shown to be extremely resistant to change (Kogut, 1996), and students will often go to great lengths to try to accommodate prior alternate conceptions. Coll and Treagust (2002) give examples where students will "change the facts" in order to make new concepts fit in with their prior alternate conceptions. Similarly, Bodner (1991) found that when students were asked why ice and the Titanic both floated on water, given that steel is almost eight times as dense as water and ice is less dense than water, the students explained that the Titanic was made from titanium, not from steel. The learners had tried to change the facts to fit in with their existing views.

Prior conceptions can influence a student's ability to understand, develop and use analogies, and are an important factor leading to the observation by Vosniadou (1994) that "... the mental models students create and use can be incomplete ... unstable ... unscientific" (p. 8). Because student prior conceptions are typically hidden and often resistant to change, researchers suggest that educators must help students expose and articulate their preconceptions and compare them with scientific conceptions, so that cognitive conflict can take place and conceptual change be initiated (Nussbaum, 1985). In a study of senior high school mathematics students, Fast (1999) found that student alternate conceptions relating to probability could be changed if the student was presented with written examples of related researcher-developed anchoring
analogies. Use of these anchoring analogies allowed students to construct understanding based on scientific conceptions. Attention to the differences between the scientific conceptions and their prior alternate conceptions produced the cognitive conflict that helped the students to reconstruct their understanding of probability concepts.

The significance of prior conceptions on students' learning with analogical models is illustrated by Coll and Treagust (2002), who carried out an interview-based enquiry in which high school, undergraduate and post-graduate chemistry students were interviewed regarding their understanding of concepts of chemical bonding, an area in which prior alternate conceptions are common (Teichert & Stacy, 2002). Students' at all three levels made use of analogies when explaining bonding, but they were also found to have prior alternate conceptions. The study indicated that in a number of cases these prior conceptions were incorporated into invalid student-developed analogies. This finding is in accord with Pittman's (1999), conclusion that students could not produce appropriate and valid analogies if they did not have sufficient scientific understanding. This situation is described by Clement (1993) as the "... paradox of prior knowledge and alternate conceptions ..." (p. 1252). The paradox lies in the fact that while students must make use of their existing knowledge in order to make sense of difficult concepts, the students' existing intuition may conflict with the concept being taught. Clement sees a solution to this dilemma in the use of teacher-led discussion and bridging analogies to produce conflict between learners' prior conceptions and the new concept, which, through discussion, can lead to conceptual change. He argues that this procedure allows alternate conceptions to be used positively, as a catalyst for conceptual change. I concur that attention to such conceptions can point to a productive way forward. Student prior conceptions are typically hidden and intractable, and any process that illuminates them is important. Thus, rather than viewing prior conceptions as a negative influence on the assimilation of an analogy, I view analogies as an important
pedagogical tool for bringing attention to prior conceptions, which can then be accommodated into new schemata. This view is supported by Duit (1991) who found that students' responses to the use of analogies can, by revealing their alternative conceptions, provide teachers with information on students' prior knowledge.

When viewed from constructivist perspectives on learning, the structure-mapping process between model and target should be expected to be less problematic if students have an intimate understanding of the analogical model being used. This condition may be met if students devise their own analogies. While there is a robust literature looking at analogy use in general, most research has focused on teachers' use of analogies. A smaller number of researchers have investigated students' use of their own analogies. Research related to student-generated analogies indicates that involvement of students in developing their own analogical models can aid in conceptual understanding (Harrison & Treagust, 2000; Khan, 2003; Wong, 1993; Zook, 1991).

An important question is whether the use of such analogies can help students to construct understanding leading to knowledge transfer. A number of studies, in which students were actively involved in constructing analogical models, inform this question.

There is evidence that students can create analogical solutions to problems that aid their understanding of science concepts (Clement, 1989; Khan, 2003). Clement (1989) studied the problem solving ability of 16 freshman engineering students when they participated in ‘thinking aloud problem solving interviews’. Students produced 96 solutions to problems. Of these solutions, 25% contained analogies that were generated by the students. While some analogies were based on alternate conceptions, and thus not fruitful, a number were found to prompt self-assessment and refinement by the students, elements indicative of conceptual change. Clement notes the similarity between the creative analogical solutions produced by some of the students and those observed in an earlier study of analogies produced by expert scientists (Clement, 1981).
Wong (1993), in a study involving eleven pre-service teachers, investigated whether students' self-generated analogies could encourage change in their understanding of a particular scientific phenomenon. Participants were presented with a target scientific phenomenon, and were asked to construct and apply their own analogies in order to address their conceptual difficulties relating to the topic. This process enabled students to 'problem find' with personally relevant material, instead of simply solving teacher-designed problems. Wong concluded that self-generated analogies led to the students extending their knowledge by devising new explanations and raising important questions relating to the phenomena under study. Wong also found that using student-developed analogies encouraged ownership of the material being studied, because students' personal analogies are often more familiar and more applied than those developed by the teacher.

Despite evidence that the use of analogies can promote conceptual understanding, analogies are not used in the classroom as often as might be expected (Thiele & Treagust, 1994), and when they are utilized, it is seldom in an effective manner (Treagust, Harrison & Venville, 1998). This is not surprising, because teachers often have no formal training in the application of analogies, and exhibit limited understanding of analogical models (Justi & Gilbert, 2002; Van Driel & Verloop, 1999). If teachers are to utilize analogies effectively, appropriate models for presenting instructional analogies are needed. In the next section, I describe a number of approaches to analogy use that have been developed to meet this need.

**Approaches for Using Analogies in Teaching Science**

A number of approaches for developing and using analogies for teaching science have been described in the literature. One approach that has proved valuable is the “Teaching With Analogies” model (TWA) (Glynn, 1991). The TWA provides a structured sequence of operations
that were identified as commonly present in well-developed analogies chosen from school science textbooks:

• Introduce the target concept.
• Cue retrieval of analog concepts.
• Identify relevant features of target and analog.
• Map similarities between target and analog.
• Indicate whether analogy breaks down.
• Draw conclusions.

These operations were also found to be common in classroom analogies utilized by exemplary teachers, and Glynn suggests that teachers and textbook authors could use analogies more successfully if they follow the sequence of operations in the TWA procedure.

Glynn’s approach has been critiqued by Harrison and Treagust (2000), who suggest applying a modified form of the TWA involving fewer steps, while also attending to the shared role of teachers and students. The approach of Harrison and Treagust, which they refer to as “Focus, Action and Reflection” (FAR), involves:

• focus on planning the use of the analogy by mapping the conceptual problem to be tackled, the students’ prior knowledge and abilities, and possible analogies that could be used
• action, in which the analogy is implemented in a cooperative process where both teacher and students map the attributes of the analogy, and how it relates to the target topic
• reflection on the success of the analogy in promoting student understanding of the target topic, and future modifications that may be necessary.

Harrison and Treagust (2000) stress the important role teachers can play in promoting conceptual learning through ‘social negotiation’ of analogies with students. Teachers must choose models and
analogies that take into account student needs, their prior knowledge, the nature of the science content and the type of explanation being used. Teachers also need to guide students in the mapping of process similarities between the model and the target.

Another strategy for analogy development which attends to students’ prior knowledge is the General Model of Analogy Teaching (GMAT), (Zeitoun, 1984). As described by Pittman (1999), this approach involves nine steps, which include:

- assessing students’ prior knowledge and background in analogical learning
- analysis of the topic to be taught and characteristics of the topic to be used in the analogy
- judging appropriateness of the analogy
- choosing a teaching strategy to present the analogy to the students
- presenting the analogy
- evaluating the effectiveness of the analogy
- revision of the above process.

While this approach was originally intended to help teachers construct analogies, Pittman (1999) has also demonstrated that the GMAT can be employed to help students to understand and learn from teacher-generated analogies, and to provide knowledge that could be used by the students when developing their own analogies. In Pittman’s study, high school biology students were first given instruction that helped them to identify relationships between the analog and target for teacher-generated analogies. When they were comfortable understanding and using teacher-generated analogies, the students were instructed on how to construct their own analogies. The instructor provided ten key terms related to the science target, and asked students to use verbs to define relationships between the analog and the key terms. Pittman found that students’ understanding of analogies, and their ability to generate meaningful analogies, was enhanced using this instructional method.
Nashon (2004) has developed a “Working with Analogies” model (WWA) which acknowledges and makes use of students’ prior knowledge. The WWA approach consists of six steps:

- Assessing students’ knowledge of the analogical model
- Assessing students’ knowledge of the target
- Identification of attributes of the analogical model and target
- Mapping of attributes/relationships between model and target
- Identifying unmapped attributes
- Drawing conclusions about the target

The WWA strategy is based on the GMAT and TWA approaches, but differs in emphasizing the need to assess students’ knowledge of the analogical model as well as of the target. The WWA also involves identifying unmapped attributes before conclusions about the target are drawn, while the TWA model reverses these steps. Nashon found that when high school physics teachers in Kenya used analogies in their classrooms, most did not attempt to determine students’ prior knowledge of the analogical models or targets, and rarely matched attributes between the model and target. These steps are important in analogical learning, and Nashon advises that before using analogies, teachers must be aware of student understanding.

While a number of researchers (Else, Clement & Ramirez, 2003; Glynn, 1991; Harrison & Treagust, 2000; Nashon, 2004 and Pittman, 1999) have produced guidelines for teachers who use analogies, few guidelines exist for the production of student-generated analogies. Harrison and Treagust draw attention to problems associated with the development of student-generated analogies. While students gain ownership through this process, their analogical models may be inappropriate because of prior conceptions, a naïve understanding of modeling, and incomplete background content knowledge. Harrison and Treagust suggest that in developing student-
generated analogies, a compromise must often be reached between student and teacher input. They propose that the teacher should develop the initial guidelines for constructing the analogy, and that guided instruction on modeling should be an important precursor to student involvement with producing analogies. They suggest that the Focus, Action and Reflection process (described earlier in this chapter) can be adapted for student use. Whether such an approach can lead to more robust understanding is open to question, and probably depends largely on the degree to which the teacher is prepared to become a facilitator of learning, rather than a disseminator of knowledge.

**Challenges Associated with Using Analogies in the Science Classroom**

If, as Duit (1991) states, learning "... fundamentally has to do with constructing similarities between the new and the already known" (p. 652), then the role of analogies, which provide precisely these links between the new (target) and already known (model) through analogical relationships, can be seen as central to the learning of science. Yet the use of analogies does not automatically produce enhanced conceptual understanding (Solomon, 1994). If analogies have such a central position in the learning process, why is their use often problematic? It appears that even when teachers accept that analogies can play an important role in learning, problems may arise during implementation within the classroom. An old saying tells us that 'you can take a horse to water, but you cannot make it drink'. I believe you can also give a student an analogy, but you cannot assume that it will aid in the construction of knowledge. Whether the use of analogies will enhance conceptual understanding is impacted by whether instructors and students understand the use of analogies. I next consider how instructor and students’ understanding of analogies relate to the implementation of analogies in the science classroom.
Teachers' Understanding of Analogical Models

Construction of knowledge does not take place within a vacuum, and theoretical perspectives such as constructivism and social constructionism remind us of the importance of the teacher in defining and affecting the learning environment. Thus, we need to consider teachers' beliefs and understanding of models and analogies.

Van Driel and Verloop (1999) found that many high school science teachers are naïve realists with respect to models and modeling, and may hold inconsistent beliefs regarding models. In order to investigate the knowledge of models and modeling held by 15 high school science teachers, Van Driel and Verloop used a Likert type questionnaire and an open-item questionnaire. The results indicated that although the teachers could produce a general description of a model, the majority had limited and inconsistent knowledge of models and the modeling process. For example, the teachers rarely mentioned the use of models to make predictions. Chemistry teachers exhibited particularly naïve understanding of modeling. For example, many considered a model to be a simplified reproduction of reality. This is illustrated by the response of one teacher, who considered both a picture of a house and a toy car to be scientific models. In fact, they are representations of reality rather than scientific models, because they do not allow construction of an analogical relationship to the target. Similarly, many teachers considered that the quality of a model was determined by how closely it corresponded to the target, rather than on its explanatory or predictive qualities. Further evidence that many teachers have a naïve understanding of models and modeling is provided by Gabel (1999), who cites a study by Dori, Gabel, Bunce, Barnea and Hameiri (1996). In this study, high school chemistry teachers were asked whether a pictorial representation of widely separated water molecules was intended to represent liquid, solid or gaseous water. Many teachers were unable to relate this microscopic model to the macroscopic phases.
In view of science teachers' limited and inconsistent understanding of modeling, it is not surprising that their students often misunderstand the implied attributes of models. Although no studies have been carried out on college instructors' understanding of modeling, it can be presumed that they will also exhibit a spectrum of beliefs and understanding. Such variation in instructors' understanding of modeling will affect the way that students perceive and use analogies, particularly when student-generated analogies are used in the classroom, where instructors must play a critical role in guiding students through the development of analogical models and the mapping of relationships between the model and the target (Harrison & Treagust, 2000).

**Differences in Teacher and Student Perceptions of Analogical Models**

When a teacher tries to match an analogy to a target phenomenon, the choice of an analogy may not be helpful for students if it is unfamiliar or confusing to them. Venville and Treagust (1997) describe a teacher's attempt to use the analogy of a city when teaching the concept of cell structure to a class of grade 8 students. Interviews of three students indicated that they had alternate understandings of the nature of a city, and while the analogy seemed to be helpful to some students, to others it appeared to be unhelpful. For example, one student compared the nucleus of a cell to a city council, the role of which she considered to be rubbish removal. She then produced the erroneous view that the role of the nucleus was to remove wastes. Venville and Treagust suggest that a more successful approach might include teachers probing deeply into students' understanding of the analog and its relationship with the target phenomenon. An alternative approach is to use analogical models that the students themselves devise. Unfortunately, although students' analogical models will be more familiar and meaningful than
those generated by teachers (Harrison & Treagust, 2000), students may transfer their alternate conceptions from the analogical model to the target.

**Students’ Reasoning Abilities**

In a study involving 77 college biology students, Lawson, Baker, DiDonato and Verdi (1993) investigated the relationship between students’ reasoning abilities and analogical learning. The students were introduced to two theoretical concepts (molecular polarity and bonding) and asked to explain an unrelated situation (mixing of dye with water, but not oil, when all three were shaken together). In their explanations, students typically misapplied the theoretical concepts when trying to explain the unrelated phenomenon. All the students were then introduced to a theoretical concept (diffusion) which was directly related to the phenomenon. A group of students, the experimental group, also received instruction on related analogical models. All students were then questioned on their understanding of the original phenomenon, to determine if any changes in understanding had occurred. Lawson, Baker, DiDonato and Verdi found that use of the analogy affected conceptual understanding, and that the experimental group who received the analogy performed significantly better on the post-test question than the control group, who did not receive the analogy.

Lawson, Baker, DiDonato and Verdi (1993) also studied the relationship between conceptual understanding and students’ reasoning abilities. Prior to the analogy intervention, students were classified as being either “intuitive”, with poorly developed reasoning skills, “transitional”, with partially developed reasoning skills, or “reflective”, with well-developed reasoning skills. Of those tested, fifteen percent of the students were classified as intuitive thinkers, sixty-five percent as transitional thinkers and twenty percent as reflective hypothetico-deductive reasoners. When the students were re-tested on their understanding of the original
phenomenon, forty percent of the ‘reflective’ students changed their response to the dye question from their earlier erroneous explanation based on molecular polarity to a correct explanation based on the correct diffusion concept. Only nineteen percent of the students classified as ‘transitional’ reasoners changed their response from the earlier erroneous explanation to the correct one based on diffusion, and none of the ‘intuitive’ reasoners changed their views from the original erroneous explanation. Lawson, Baker, DiDonato and Verdi conclude that successful application of the new concept required well-developed reasoning abilities. These skills are important for successfully mapping the structures that link an analogical model to the target (Gentner & Markman, 1997).

**Attention to Surface Details**

The inability of many students to transfer their understanding from the prescribed analogical model to the target (Biggs, 1982; Gick & Holyoak, 1980) has been related to students’ blinkered concentration on surface details and features of the analogical model, and their inability to distinguish the important relationships between the model and the phenomenon that it describes. Duit (1991) notes that while the inferential powers of an analogy are governed by higher order structural relationships, accessibility of the analogy is governed by lower-level literal or surface similarities. The danger of this relationship is that, although surface similarities between the model and target are important in initial recognition and selection of an analogue, these similarities may obscure more important relational structures (Zook & DiVesta, 1991). Thus, novice learners may be unable to identify important relationships between the model and target, and be unaware of constraints that must be applied to the mapping process that takes place between the model and target (Zook & DiVesta).
These problems may arise because novice learners may believe that a one-to-one relationship exists between the model and the target (Dyche, McClurg, Stepans & Veath, 1993; France, 2000; Thiele & Treagust, 1991). Also, there are always some aspects of the analog that do not ‘fit’ the target, and which can mislead students. Hesse (1966) has referred to these as negative analogies. In addition, analogical transfer can be inhibited when teacher-generated analogies are unfamiliar to students (Treagust, Harrison & Venville, 1998). In such cases novice students may fail to recognize the important structural and relational similarities and differences between the analogy and the target. There are therefore many reasons why students may transfer surface properties from the analogical model to the target (Gentner, 1989).

The ‘modeling abilities’ of students can also affect whether students attend to superficial details in analogies (Grosslight, Unger, Jay & Smith, 1991; Harrison & Treagust, 2000). Grosslight, Unger, Jay, and Smith classified learners as:

- level 1 modelers, who view the model as an exact representation of the target
- level 2 modelers, who can differentiate between the model and the target, but who use the model only as a way of explaining limited features of the target, or
- level 3 modelers, who use models as thinking tools which can be manipulated to allow extension of knowledge.

Grosslight, Unger, Jay, and Smith (1991) used this method of classification to determine the modeling abilities of high school students. They found that 7th-grade students of mixed ability were level 1 modelers, and 11th-grade honors science students were either level 1 or level 2 modelers. The findings of Grosslight, Unger, Jay and Smith hint that modeling ability can develop with age. However, many college science students continue to have a naïve understanding of modeling (Coll & Treagust, 2002).
Because of the demonstrated relationship between student modeling ability and conceptual understanding (Grosslight, Unger, Jay & Smith, 1991; Harrison & Treagust, 2000), it is important that students possess or acquire well-developed modeling skills. Teachers can play important roles in improving these skills, by choosing models and analogies that take into account student needs, their prior knowledge and the complexity of the science content. Teachers also need to guide students in the mapping of process similarities between the model and the target. As suggested by Harrison and Treagust (2000), guided instruction on modeling should be an important precursor to student involvement with producing analogies, with processes such as Focus, Action and Reflection (discussed earlier) being adapted for student use. Harrison and Treagust suggest that a compromise must often be reached between student and teacher inputs. They suggest that initial guidelines for constructing the analogy should come from the teacher, that guided instruction on modeling should be an important precursor to student development of analogies, and that students' modeling skills can be developed if teachers sequence their use of models so that students are challenged with progressively more abstract models.

Summary

Research has indicated that analogies are powerful tools that promote students' construction of understanding of new concepts based on their existing knowledge (Duit, 1991). The advantages of using analogies, particularly for student-generated analogies, include the ability to promote interest, ownership and deeper conceptual understanding of science (Harrison & Treagust, 2000; Wong, 1993; Zook, 1991). Analogy use also encourages teachers to attend to students' prior knowledge, and may reveal students alternate conceptions (Coll & Treagust, 2002). Despite these advantages, analogies are not commonly used to promote understanding within the science classroom (Treagust, Duit, Joslin & Lindauer, 1992). This is
surprising, because the use of analogies has an established role in the understanding of science (Schön, 1979), and analogies are familiar and accessible to instructors (Dagher, 1995; Thiele & Treagust, 1994). Treagust, Duit, Joslin and Lindauer suggest that this lack of analogy use may result from teachers having an insufficient repertoire of analogies to draw on, and being uncertain how to use analogies effectively.

While there is a robust body of literature describing the use of teacher-generated analogies in the science classroom, little research has been conducted on the use of student-generated analogies. However, this limited research indicates that involvement of students in developing their own analogue models can play a particularly important role in promoting conceptual understanding (Harrison & Treagust, 2000; Khan, 2003; Wong, 1993). For example, Wong found that self-generated analogies could encourage change in students’ understanding of particular scientific phenomena, and that students could extend their knowledge by devising new explanations and raising questions relating to the phenomena being studied. Wong also found that student-developed analogies encourage ownership of the material being studied, because students’ personal analogies are often more familiar and more applied than those developed by the teacher.

It is important to note that the use of analogies does not automatically enhance learning. Researchers have found that novice learners may transfer surface properties from the analogical model to the target, (Gentner, 1989) and may believe that a one-to-one relationship exists between the model and the target (Thiele & Treagust, 1991; Dyche, McClurg, Stepans & Veath, 1993; France, 2000). In addition, analogical transfer can be inhibited when teacher-generated analogies and textbook analogies are unfamiliar to students (Treagust, Harrison & Venville, 1998). In such cases novice students may fail to recognize the important structural and relational similarities and differences between the analogy and the target. Zook and DiVesta (1991) note that although
surface similarities between the model and target are important in initial recognition and selection of an analogue, these similarities may also obscure more important relational structures.

The use of analogies in the science classroom can be enhanced in a number of ways. Models such as the GMAT (Zeitoun, 1984), TWA (Glynn, 1991) and FAR (Harrison & Treagust, 2000) have been developed to aid in the construction and use of instructional analogies. In addition, students may need guidance in using analogies, and in mapping important similarities between the model and the target (Zook & DiVesta, 1991). Harrison and Treagust suggest instruction on modeling, based on the FAR model, should be a precursor to student involvement with producing analogies. However, these approaches are not widely used by instructors, and despite the documented usefulness of student-generated analogies in promoting understanding (Harrison & Treagust, 2000; Khan, 2003; Wong, 1993), the literature contains few examples that demonstrate how student-generated analogies can encourage learning within the science classroom. Many illustrative examples are needed, because whether instructors choose to accept and adopt innovative strategies appears to depend on whether they view a strategy as fulfilling the pedagogical requirements of clarity, quality, fruitfulness and practicality (Fullan, 2000). Thus, a primary objective of my research is to provide such an example.

While a principal objective of my research is to provide an example of the use of student-generated analogies in the science classroom, I am also aware that other pedagogic approaches can encourage more student-centered learning. For example, involvement in communal and small group activities (Collins, Brown & Newman, 1989; Duncan & Dick, 2000; Khan, 2006; Lundberg, 2003; Yu & Stokes, 1998; Yuretich et al., 2001), and the coupling of science with drama through what has been termed “performative inquiry” (Fels & Meyer, 1997), have been shown to be of value in enhancing social and community interactions, and in promoting meaningful learning in the science classroom. Although the effectiveness of these approaches
has previously been considered separately, the value of combining these instructional strategies in the post-secondary science classroom has not been examined. It is in this space that I place my study. The goals of my research are thus to build on the demonstrated benefits of these individual approaches, and to provide insight into the following questions:

1. In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?

2. What are the perspectives of college students and instructors on learning science using performed analogies?
CHAPTER FOUR
METHODOLOGY

This study investigated using student-generated and performed analogies as a pedagogical approach for promoting understanding of science concepts in the undergraduate classroom, and documented students’, instructors’ and my own perspectives and experiences relating to the use of this strategy. My specific research questions were:

1. In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?
2. What are the perspectives of college students and instructors on learning science using performed analogies?

In this chapter I describe the context of the study, including the university-college setting, the courses in which I conducted the research study and the participants, both students and instructors, involved in the study. I also detail the research methods I used to collect and analyze data. The last section of this chapter examines some of the limitations relating to the research methods, and I conclude with a personal reflection on my interwoven roles as researcher and instructor.

Context of the Study

I carried out this study at a university-college in British Columbia. During its thirty-year history, this institution has undergone significant expansion in terms of number of students and programs provided as it developed from a community college offering two-year university transfer programs to a university-college offering four-year undergraduate degrees. My research was conducted between January 2003 and December 2004. At this time the institution enrolled
approximately 5600 students and offered twelve different bachelor degrees, with twenty-two different majors, as well as numerous certificate and diploma programs.

My study was conducted in two first year biology majors courses, each enrolling twenty-nine students; two sections of a first year biology course for arts majors, one with fourteen students and one with ten; and two college preparatory chemistry courses, one with fourteen students and one with nineteen students. Fifty students enrolled in three sections of a college preparatory chemistry course served as a comparison group. Courses were taught over a thirteen-week semester, meeting twice a week for eighty-minute lectures and once a week for three-hour lab sessions.

The Research Study Participants

The Instructors

Three college instructors, Steven, Anne and Sue (pseudonyms) participated in the study. These were instructors who had indicated to me they had an interest in using innovative teaching approaches in their classrooms. All three were involved in teaching both lower- and upper-level post-secondary science courses.

Steven

Steven holds a bachelors degree and a doctoral degree in chemistry, and had been teaching undergraduate and college preparatory level chemistry courses for twenty-six years at the time the study was conducted. He describes his primary mode of teaching as lectures, during which he expects students to participate by asking and answering questions. In his classroom, Steven’s teaching emphasis is on promoting understanding of concepts, rather than on rote memorization and algorithmic calculations. Before participating in this study he had used
teacher-generated analogies for twenty-five years. Steven viewed his use of analogies as a productive strategy for holding student interest and for helping students to understand difficult concepts (although he had never examined how and whether his use of analogies accomplished this). Steven was aware of problems associated with using a strictly lecture-based transmission mode of teaching, and he indicated he was interested in trying strategies that might encourage more student-centered learning.

Anne

Anne holds a bachelors degree in biology and a doctoral degree in science education. At the time this study was conducted, she had been teaching undergraduate biology classes for approximately twenty-five years, and described her teaching approach as a mixture of collaborative learning and lectures. Anne regularly uses problem-based learning in her classes and indicated that her students have told her that they value this strategy; many of them aspire to study medicine and think that the problem-based approach will be applicable to their future studies. Anne is aware of recent educational research and very interested in trying out new teaching and learning strategies.

Sue

Sue holds bachelors and masters degrees in biology, and had been teaching preparatory and undergraduate biology for fifteen years when this study began. Sue had been a part-time instructor for most of this time, but had assumed a full teaching load the year I invited her to participate in my study. Her primary mode of teaching is lecture interspersed with problem-solving exercises. She had frequently used teacher-generated analogies in her classes and was interested in trying student-generated analogies in lab periods or tutorials. Sue indicated that she
feels pressured to cover the course content, and constantly struggles to find ways of presenting the large body of information that represents the required curriculum of an upper level biology course.

The Students

The students in my study were undergraduates enrolled in Steven, Anne, and Sue's first year and preparatory science courses. One hundred and sixty-five students enrolled in these courses participated in the study. Approximately 90% of these students were Caucasian, with the only other ethnic groups being Indo-Canadian and Asian. English was the first language of the majority of the students, and all students were fluent in English. Approximately 80% of the students in the preparatory chemistry courses and the first year biology courses for arts majors were female. In the two sections of first year biology majors courses, approximately 70% of the students were female. Twenty-seven of the students agreed to be interviewed. Interviews took place after the analogy activity.

Methodology of the Study

Naturalistic Case Study

My objective was to gain an in-depth understanding of how student-generated and performed analogies could be used in the university-college science classroom, and to determine whether this learning strategy could enhance conceptual understanding. My specific research questions were:

1. In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?
2. What are the perspectives of college students and instructors on learning science using performed analogies?

To gain an understanding of the use of analogies within the setting of the post-secondary science classroom I used a naturalistic case study approach. Case study methodology was deemed appropriate because of its attributes. Yin (1994) defines case study as "... an empirical inquiry that investigates a contemporary phenomenon within its real-life context ..." (p. 13). In my study, the phenomenon being inspected was the implementation of specific pedagogic activities within the real-world setting of the college science classroom. Case study is useful for study of a phenomenon that is bounded, or limited to a finite and defined system (Merriam, 1998). These boundaries delineate all aspects of the study including who is involved and the time allocated for the study. My case study involved five post-secondary classes, three instructors and one hundred and sixty-five students, and the time frame involved was restricted to one semester for each class.

Stake (2000) identifies three types of case study: the "intrinsic case study", undertaken for a better understanding of a specific case; the "instrumental case study" which provides insight into an issue or redraws a generalization; and the "collective case study", made up of a study of a number of cases and carried out in order to investigate a phenomenon. My research took place in a number of different science classes each of which could be viewed as an individual case, and examined a specific pedagogical phenomenon taking place in all the classes. Thus, my research can be considered a collective case study. Collective case studies are powerful because understanding a number of cases can facilitate overall understanding of the research topic. Miles and Huberman (1994) observe that:

"By looking at a range of similar and contrasting cases, we can understand a single-case finding, grounding it by specifying how and where and, if possible,
why it carries on as it does. We can strengthen the validity, and the stability of the findings” (p. 29).

The utility of collective case studies is also supported by Merriam (1998), who notes that the use of multiple cases is a common strategy for enhancing the validity and generalizability of findings.

Merriam (1998) characterizes qualitative case studies as particularistic, descriptive and heuristic. A study is particularistic in that it focuses on a defined situation, event, program or phenomenon. It is descriptive because it produces a “...rich, ‘thick’ description of the phenomenon under study” (p. 29), and it is heuristic because it “…illuminates the reader’s understanding of the phenomenon under study” (p. 30). My case study was particularistic in the sense that I focused on a specific pedagogical phenomenon – the use of analogies in the post-secondary science classroom and the experiences of those involved. It was also descriptive, as I documented the events and my experiences, as well as those of other participants, through detailed characterizations, to aid understanding of the phenomenon under study. My case study was heuristic in that my analysis of the comprehensive data set allows the reader to gain deeper insight into the undergraduate science classroom, and consider whether my findings are transferable to their own situation (Merriam, 1998).

Merriam (1998) points out that case studies do not require particular methods for data collection and analysis, while Stake (2000) notes that case studies can involve both qualitative and quantitative research methods. To answer my research questions, I used a combination of quantitative and qualitative research methods which is consistent with a case study methodology.
Methods

General Intervention Procedures

Three months before the semester I approached four instructors to determine whether they wished to be participate in my study. All the instructors had previously indicated an interest in investigating new teaching approaches. One instructor declined to participate due to her heavy workload but expressed interest in participating at a later date. The three other instructors, Steven, Anne and Sue all agreed to participate in the analogy activity.

A few weeks before the start of semester I met with the instructors of each course (Steven, Anne and Sue) to discuss topics that were suitable for student-generated and performed analogies. We decided that science concepts the instructors had previously identified as “difficult” (i.e. complex or abstract) would be chosen for the student analogy activities. Following identification of topics for the interventions, I arranged a schedule with each instructor that allowed me to attend and observe their classes during their teaching of the topic that would be used for the analogy activity.

My first meeting with each class took place midway through the semester, before the instructor covered the analogy topic in class. At the first class meeting, I gave a presentation of approximately fifteen minutes, in which I explained the purposes and methods of the study. This included my explanations of the concepts of analogy, model and target, as well as the relationship among these concepts. I pointed out that analogies are considered to be a useful tool for helping learners gain understanding of new ideas by allowing them to work with and apply the knowledge they already have. In introducing the terminology ‘model’ and ‘target’, I emphasized that the already-understood model is used to aid in the understanding of the new topic (the target). I explained that the important property of an analogy is the links (or
relationships) that exist between the model and target. I cautioned students not to expect the model and target to be identical, or even similar in all respects. I also gave the students guidance on the generation of analogies, following the approach of Wong (1993). I emphasized that it was important to develop their analogies by using a model that they were familiar with, and that they could choose any model they wanted. I also explained that part of the analogy development process involved evaluating the model to determine whether it represented important relationships to the target scientific phenomenon, and that they might have to modify the analogy as necessary.

Following this short lesson on analogies I explained the activity they would be participating in. I told students that they would form small groups to discuss analogies developed by individuals in their group and choose one analogy for refinement and performance for the class. I tried to emphasize the importance and value of their physical involvement in the learning process by reference to "The Cone of Learning" (Dale, 2002), which I provided as a hand-out. The handout indicated that retention of new knowledge in long-term memory is related to whether the learner is engaged in passive or active learning. I emphasized that active learning, which may incorporate physical involvement in a dramatic presentation, a simulated event or participation in an authentic practice, is believed to lead to new knowledge being integrated into long-term memory. During this first meeting with the class, I handed out consent forms and explained that by signing the form they would be consenting to be audiotaped and videotaped during the analogy exercise. I also mentioned that they would also be consenting to my examination of their in-class materials and answers to pre- and post-intervention probe and test questions relating to the analogy. Students could also indicate on the consent form whether they were willing to be interviewed after the intervention. I stressed that confidentiality would be
maintained, and students would not be identified by name. After handing out the forms, I responded to any questions that arose.

Shortly after this initial meeting with the students, I again met with the instructors to define and clarify their roles during the intervention. The instructors' responsibilities included establishing groups of four or five students for the analogy activity and devising, administering and collecting a set of pre- and post-intervention probe questions that would assess students' understanding of the science topic. The questions devised for two classes are described later in this chapter. Instructors also agreed to facilitate a post-intervention discussion of the analogy performances with the class, during which non-science conceptions and aspects of the topic students found confusing could be addressed, and the relationships between the analogy and the target concept discussed.

After the science concept pertinent to the analogy exercise had been taught in class, each instructor directed the analogy activity. Students were told to individually devise an analogy that related to the science topic, keeping in mind their analogy could be performed by a group of four or five students. Instructors gave each student a handout which provided the following instructions:

*Please record below (in as much detail as possible) your ideas on how your group could model (science concept X). Your group will discuss each person's idea in order to decide which could be acted out in class. Please bring along any suitable props.*

Students were told to bring their written ideas with them to the next class for the discussion and activity.

During the next class, each instructor assigned students into small groups (typically five students in a group). Two instructors (Sue and Steven) made this assignment randomly, while
Anne allowed students to work in groups that had previously been formed for other small-group activities. Each group was given forty-five minutes of class time to meet and share their individual analogies. During this time the group was to choose one analogy they would develop and present to the entire class, and finally to rehearse the presentation. I asked each group to identify one member, who would record details of the analogy exercise. I gave each recorder a sheet of paper containing the following instructions:

1. Write your group’s ideas, giving as much detail as possible, for modeling the (science concept).

2. Your group can make any props and try a trial run through of their chosen analogy, making any adjustments as necessary.

3. Group recorders should note your group’s responses to the other groups presentations, giving as much detail as possible. Also say why or why not you thought they were helpful for learning this concept and which were closest to the text/notes given in class. Write any comments below.

Groups then performed their analogies, with the remaining class members acting as the audience. The audience were directed to view each performance critically, and to be prepared to discuss how closely the analogy related to the science concept after the performances. Each analogy performance was videotaped. Presentations were followed by in-class discussion of the performed analogies that involved all students and the instructor. The specific class procedures differed for each instructor, and are detailed in the next section. A timeline for the research study events is given in Table 4.1 (see page 74).
Specific Procedures

Analogy use in Anne's biology classes.

Anne’s first effort at using student-generated analogies took place in March 2003. She decided to work with her first year biology majors students on the topic of ‘the immune response’. Anne selected this topic because she had observed that students had difficulty learning the complex multi-step processes and terminology associated with the body’s immune system. A description of the body’s immune response is given in Appendix A. Twenty nine students from Anne’s course developed, performed and discussed immune response analogies following the general procedures described earlier. These activities took place during a regularly scheduled eighty-minute period, three days after Anne had given an eighty-minute lecture presentation on the topic. In preparation for that lecture Anne asked students to read a chapter on the immune response in their textbook. To assess students’ initial knowledge of the immune response, Anne devised a pre-intervention probe question relating to the immune response (see page 77). Anne gave the pre-intervention question to her students on the day of the analogy activity, immediately prior to the group planning activity. Anne informed her class that their responses would not be graded and allowed students to work individually for ten minutes on the question, after which she collected their responses. Four days after the analogy performances Anne handed out a post-intervention probe question (see page 78). Anne again informed students that their responses would not be graded, and allowed them to work for ten minutes on their answers. Anne and I reviewed students’ responses to the pre- and post-intervention questions after the analogy intervention was completed. Working with Anne I developed an answer key and method for coding students’ responses (see Analysis Section, pages 78-79).
In February 2004, Anne chose ‘nuclear control of root growth’ as the topic for a second student-generated analogy activity she would conduct with another class of first year biology majors students. Anne selected this topic because she was interested in whether students would be able to apply knowledge of cellular processes, which had been taught the previous semester, to the new topic of root growth. A description of the development and growth in a plant root cell is given in Appendix B. Twenty-nine students in Anne’s lecture section were enrolled in two tutorial groups, which met at different scheduled class-times. All fifteen students in one tutorial group participated in an activity in which they developed, performed and discussed analogies that related to the root growth topic. The other tutorial group did not participate, and served as a comparison group. These students discussed the root growth topic in small groups during their tutorial with Anne.

Analogy activities took place during a regularly scheduled eighty-minute tutorial period and followed the general procedures described earlier. Anne did not lecture on the topic of root growth prior to the intervention, but the week before the intervention she assigned reading in their textbook covering the relevant material. Three days prior to the intervention she handed out a diagram, showing the development and growth in a plant root cell, for students to supplement their reading in the textbook. Anne devised and gave a pre-intervention question on nuclear control of root growth to the class on the day of the analogy activity, immediately prior to the activity. The pre-intervention question Anne used to probe students’ understanding is shown in Appendix B. Anne again informed the students that their responses would not be graded. Students worked for ten minutes on their answers and their responses were collected before the analogy performances. Anne intended to give the students a post-analogy question on the final exam, but later decided not to include this topic.
Analogy use in Sue’s biology classes.

Sue decided to introduce students in her first year biology course for arts majors to the analogy activities. These students were enrolled in two laboratory sections that were combined into one larger section for lectures. Sue chose the topics of mitosis and meiosis for the analogy activity because she had observed that students had difficulty learning these multi-step processes, could not differentiate between the two processes, and confused the related terminology. A description of mitosis and meiosis and related terminology is given in Appendix C.

Twenty-four students from Sue’s course participated in a mitosis/meiosis activity in which they developed, performed and discussed analogies. The intervention procedures were those described earlier. Six days before the analogy intervention Sue asked the students to read the relevant chapter in the textbook and gave a lecture on mitosis and meiosis. The analogy activity was conducted in two laboratory sections, one with fourteen students and one with ten students. Students in both sections completed an unrelated laboratory exercise on reproduction which lasted eighty minutes, immediately before the analogy activity. Sue devised pre- and post-analogy questions to probe students’ understanding of the topic (see Appendix C). She handed out the pre-intervention question in class immediately prior to the activity and informed students that their responses would be graded. After ten minutes (just prior to the analogy activity) she collected the responses and scored these after the class. Sue gave the post-intervention question to the class seven days after the analogy activity, as part of a mid-term test. She graded the students’ responses, and passed them on to me.

Analogy use in Steven’s chemistry classes.

In June 2003 Steven chose the topic of kinetic molecular theory and the behavior of gases for an analogy activity in his first year preparatory chemistry course. He selected this topic
because he had observed previously that students had problems relating the microscopic behavior of gas molecules to the macroscopic properties of gases. A brief description of the kinetic molecular theory of gases is given in Appendix D.

Fourteen students from Steven’s course, working in groups of four or five, developed, performed and discussed analogies related to the behaviour of gas molecules under differing conditions of temperature and pressure, following the same procedures as students in Sue and Anne’s classes. Steven lectured on the selected topic three days prior to the analogy intervention and did not assign reading from the textbook. To determine whether students entered his class with alternate conceptions relating to the behavior of gas molecules he used two pre-intervention questions, adapted from Nussbaum (1985), and Nurrenbern and Pickering (1987). These questions were used as an in-class assignment given on the day of the intervention, before the analogy activity was explored. Steven did not assign marks and the responses were retained for later analysis. Steven also used three post-intervention questions, which were given on the final exam that students wrote six days after the intervention. He used the same two pre-intervention questions, and added a third question on the kinetic molecular theory of gases to determine whether students could demonstrate an understanding of the continuous motion of gas molecules. A description of each analogy that was devised and performed by Steven’s students is included in Appendix D, as are the questions Steven used to assess students’ understanding before the intervention and the exam questions he used to probe students’ understanding on the science topic.

In June 2004, Steven organized another analogy activity for a first year preparatory chemistry class. He identified the relative oxidizing power of a group of related elements, the halogens (fluorine, chlorine, bromine and iodine) as a suitable topic because he had previously noticed that students used an inappropriate (i.e. alternative) science conception when answering
test questions about halogens. An explanation of the scientific concept of the relative oxidizing power of the halogens is given in Appendix E.

Steven taught his four sections of first year chemistry a unit on periodic trends, dealing with the properties of different elements and how these were related to their relative positions in the periodic table. Following this, Steven taught the halogen topic during two eighty-minute lectures and did not assign reading from the textbook. The analogy intervention took place three days after this. Nineteen students from one section of Steven's course (designated as the experimental section) participated in an activity in which they developed, performed and discussed analogies related to the halogen oxidation topic. The activity, including the follow-up discussion, lasted eighty minutes and followed the same procedures as those described earlier.

Fifty students in the other three sections of Steven's course served as a comparison group. These students were taught the halogen topic in the same manner by Steven, but did not have a meeting with me to discuss analogies. Instead, Steven presented an analogy he devised to illustrate the halogen oxidation series concept. His analogy involved children fighting over candy. The children represented halogen atoms and the candy represented electrons. If the weaker child had candy, the stronger child would take the candy. If the stronger child had candy, the weaker child would be unable to take it. In both situations the stronger child ended up with the candy. After presenting the analogy, Steven explained to the students the similarities and differences between the analogy and the science concept, and entered into a discussion with the students on how results from a related laboratory experiment could be interpreted using these

\[eqn\]

2 The alternate conception students tried to use related to the 'octet rule', which attributes stability of atoms and ions to certain electron configurations.
ideas. The total time spent on presenting the instructor-generated analogy and in related
discussion was eighty minutes.

For his halogen analogy activity, Steven decided not to use pre-intervention questions. To
assess students' conceptual understanding of the topic; he included two questions on the final
exam, which was administered ten days after the intervention. One question dealt directly with
understanding of the halogen topic. A second question assessed students' ability to apply
knowledge gained during the halogen unit to the related topic of electron affinity. Steven marked
students' answers to these exam questions, and passed them to me on completion of the
semester. The exam questions Steven used are shown in Figure 4.3.

Data Collection Procedures

To obtain information on students' and instructors' experiences with, and views on, the
use of analogies and their value as a pedagogical strategy, I employed three primary methods of
data collection. These were semi-structured interviews of students and teachers, in-class
observations and collection of students' documents. All data was collected between January

Semi-structured Interviews

A primary source of data for this study was a set of semi-structured interviews. By using
a semi-structured format I was able to ask all the interviewees the same standard questions, while
allowing the conversation to take a unique direction if necessary (Merriam; 1998). I interviewed
students once, within two weeks of completion of the in-class analogy enactments. I interviewed
each of the three teachers twice. One interview was conducted immediately after the analogy
activity and a second interview was conducted about six months later. I used the later interviews
to investigate whether the teachers’ views on learning and on the use of this strategy had changed. Each student and teacher interview lasted between 45 and 60 minutes. During this time, I focused on the interviewees’ perspectives and experiences with the performed analogies, including their views on whether they saw value in performance-based activities as a learning device, and whether they viewed such activities as having a place in their science classroom. I also inquired about their general views on learning in the science classroom, and asked students whether they believed the analogy activity had advanced their understanding of the science concept. I noted whether students or instructors recognized any conceptual confusion emerging during the analogy performances. Because participants are often unable to recall specific details of activities and interactions in which they were involved, I used videos of the performed analogies for stimulated recall (Tuckwell, 1980) in the interviews of both students and teachers. Stimulated recall helps participants relive the experience, and provides opportunities for reflection and analysis of the original event. Thus, stimulated recall allowed me to gain a better understanding of my participants’ perspectives on the analogy enactments.

Student and teacher interviews were audiotaped and transcribed. I then invited students and teachers to review their transcriptions, and asked them to edit or delete responses that they did not want to have included in the study. Those participants who offered feedback clarified some minor points, and sent their edits and comments to me by e-mail. This strategy not only permitted participants to reflect further about the process they had participated in, but also allowed me to clarify some unclear responses and aided me in my analysis of the data.
Observations

Classroom observations, both prior to the analogy activity and during the activity, provided direct information about the use of student-generated analogies and helped me to contextualize and interpret my findings. Consistent with the approach suggested by Merriam (1998), I kept written records of the physical setting as well as participant activity. I audio-taped classes I observed and took digital photographs of the students as they performed their analogies to help me contextualize my notes. Video recordings of the performed analogies, used later for stimulated recall during participant interviews, further supplemented my observational data.

My observations focused on the activities, actions and interactions of participants and conversations that took place in the classroom. I made note of whether each instructor used a predominantly teacher-centered approach, centered on lecturing, or encouraged more student-centered approaches to learning, such as small-group activities. I observed groups of students as they developed their analogies and presented their analogy performances. I also noted whether students asked any questions of the instructor and whether the use of the analogy strategy evoked further questions.

I observed interactions among students in their groups as they worked together to produce their analogies. I noted whether any one person dominated the discussion or assumed a teacherly role, or whether all members of a group contributed. During conversations between participants, I noted who talked to whom, what was said and how they behaved in relation to one another. As well as describing the roles of individual actors, I also tried to obtain a second perspective by moving the focus of my observations away from the actions, conversations and interactions of individuals, and towards viewing the classroom and its participants as a whole. I
also considered "What does not happen - especially if it ought to have happened" (Merriam, 1998, p. 98).

I was interested in observing how the post-secondary students would respond to the use of a performance-based strategy in the science classroom, whether they would value this activity, and how they would communicate their understanding as they acted out their analogies. Analogy performances involve an embodied approach to learning which integrates the senses, perception, mind/body action and reaction (Matthews, 1998), in contrast to traditional science teaching, which has been dominated by the separation of cognitive knowledge from embodied knowledge. As noted by Sheldrake and Fox (1996), "... the idea that scientists are somehow disembodied – not bodily or emotionally involved in what they are doing – is part of science today" (p.17).

I also wanted to observe in what ways students would communicate their understanding of the science topic through their analogies. Knowledge is not value-free, but is largely shaped by our experiences, backgrounds and socio-cultural habits (Green, 2000), and I hoped the use of performance in the science classroom would encourage students to realize this point. As they worked with their peers to imagine and enact their own analogies, there was the potential for individual and social interpretations, which could provide opportunities for new understanding grounded in experiential knowing (Fels & Meyer, 1997).

In this study, I experienced the dual role of the researcher that Merriam (1998) describes, in which researchers are rarely just observers or participants. As participant and observer I could not help but affect, and be affected by, the setting. During the activity I tried to remain a neutral observer, and did not comment to students on strengths or weaknesses of their analogy performances. I was also careful, after giving initial directions on analogy development, to avoid taking on the role of an instructor directing the class activity. Despite my attempts to minimize my influence on the activity, I could not avoid affecting, and being affected by, the other
participants. Thus, while I recorded my thoughts on the in-class activities, including what I said and did to understand the intervention as an insider while describing it for outsiders, I recognized that any detailed account of my observations would be influenced by my perspective as both researcher and actor.

**Students’ Documents**

To understand participants’ use of analogies as a means of learning complex science concepts, I examined students’ written records of their own analogies, produced as a take home exercise before group discussions in class, and their written comments on their group’s chosen analogies. I also collected and examined students’ written comments relating to analogies performed by other student groups. To evaluate how and whether students’ participation in the analogy activities influenced their understanding of science topics I examined their responses to pre- and post-intervention probe questions relating to the analogy topic, and their answers to examination questions that related to the analogy topic.
Table 4.1: Analogy Topics and Timeline for the Research Study Events

I have outlined the timelines involved for each course below:

<table>
<thead>
<tr>
<th>Course</th>
<th>Event #1</th>
<th>Event #2</th>
<th>Event #3</th>
<th>Event #4</th>
<th>Event #5</th>
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</thead>
<tbody>
<tr>
<td>Event #1 Biology first year science major's</td>
<td>Biology first year science major's (Anne)</td>
<td>College preparatory chemistry (Steven)</td>
<td>Biology first year for arts majors (Sue)</td>
<td>Biology first year science majors (Anne)</td>
<td>College preparatory chemistry (Steven)</td>
</tr>
<tr>
<td>Event #2 College preparatory chemistry</td>
<td>Immune response</td>
<td>Effect of temperature, pressure on behavior of gases</td>
<td>Mitosis and meiosis</td>
<td>Role of the nucleus in plant cell growth</td>
<td>Oxidizing ability of the halogens</td>
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<tr>
<td>Event #3 Biology first year for arts majors</td>
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<tr>
<td>Event #4 Biology first year science majors</td>
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<td>Event #5 College preparatory chemistry</td>
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</table>

My initial contact with instructor to plan timelines for analogies. January 2003 April 2003 April 2003 January 2004 April 2004

I met the class and handed out ethics forms. March 2003 May 2003 May 2003 January 2004 May 2004

I observed lectures on the analogy concept. March 2003 May 2003 May 2003 February 2004 June 2004

Instructor gave probe questions on the science concept. March 2003 May 2003 June 2003 February 2004 n/a

I met with students to talk about analogies. The instructor gave analogy take-home assignment to students. March 2003 May 2003 June 2003 February 2004 June 2004

Instructor assigned students to groups for discussion and development of one analogy. March 2003 May 2003 June 2003 February 2004 June 2004

Students rehearsed and performed their analogy for the class, followed by class discussion of analogies and their relationship to the science concept. March 2003 May 2003 June 2003 February 2004 June 2004

Instructor gave post activity probe question on science concept to the students. March 2003 June 2003 June 2003 n/a June 2004


**Analysis of Data**

This research involved case study where I examined the use of analogies by three instructors in five classroom settings. I combined multiple data sources to obtain a holistic and comprehensive perspective on the use of student-generated and performed analogies in the post-secondary science classroom. To address my first research question relating to the ways in which the analogy intervention can help students understand complex and abstract science concepts, I carried out an in depth analysis for two cases, one biology case and one chemistry case. These were chosen to be representative of the analogy activities because in both cases sufficient time was available to carry out each event in the analogy exercise. Analysis of these cases involved examination of students' responses to probe and test questions, in conjunction with other documents and interview data. To address my second research question, relating to the perspectives of students and instructors on learning science through student-generated and performed analogies, I analyzed data from all five cases, allowing a cross-case comparison of student and instructor interviews and of in-class observations, together with my own reflections. In the section that follows, I describe how I analyzed and interpreted these data.

**Analysis of interviews and recordings**

I transcribed student and teacher interview tapes, then I searched for recurring patterns of phrases, themes and ideas using the constant comparative method (Lincoln & Guba, 1985). Based on these recurring patterns and the interview protocol, I established a number of conceptual categories. I added further categories that emerged as I transcribed additional interviews. Using these categories I coded all interview transcripts as suggested by Miles and
Huberman (1994). I also recorded my thoughts and interpretations relating to the data, and reviewed written transcripts for themes related to those found previously.

I transcribed and coded audiotapes of class events and selected excerpts of audio and video recordings of the analogy enactments. I used this data, together with my observations and document analysis, to confirm and clarify any emerging themes. I also used these data to construct a number of concept maps that helped me to search for connections among the different types of data and the emerging themes.

**Analysis of students’ documents**

I analyzed students’ written records of their own analogies, produced as a take home exercise. I also analyzed students’ written comments on their group’s chosen analogies, and their written comments relating to analogies performed by other student groups. This helped me to understand how students viewed this activity as a learning activity and whether they understood the science topic and each others’ analogy performances.

**Analysis of observations**

Throughout my research, I kept a journal, in which I recorded my personal perspectives on the analogy activities. I used these observations for triangulation with video recordings and student and instructor interview responses. I also used these data to help with recall on how the different actors – students, instructors, and myself as researcher and colleague – interacted within the classroom setting.

One method of analyzing descriptions of complex interactions is through the use of vignettes. A vignette provides “a picture or description of a situation . . . (that) can help capture
the essence of a classroom situation” (Veal, 2002, p. 1). Vignettes can “serve as a springboard for discussion” (Campbell, 1996, p. 4), and have been used to promote understanding and stimulate reflection on practice within the science classroom (Smith, 1994). Vignettes have also been used as tools in qualitative research, where they can provide the rich descriptions necessary for case study research (e.g. Davis, 1997; Koballa & Tippins, 2000; Miles, 1987; Veal, 2002), and allow the reader to experience the research setting. For these reasons I decided to develop a series of vignettes in which I tried to capture the essence of the classroom events. This allowed me to gain insight into the complex interactions that took place during the analogy activities, while also helping the reader to experience the research setting. My vignettes are presented as scenes in a short play, in chapter 5.

**Quantitative Data Analysis**

*Analysis of students’ immune response data.*

As mentioned previously Anne used pre and post-activity questions to evaluate her students’ understanding of the immune response. Anne’s pre-intervention question is shown in Figure 4.1.

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Cancer cells are continually being produced in human bodies but are usually destroyed within 4-10 days. Describe the details of the process whereby your immune system detects and destroys cancer cells.
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Figure 4.1. Anne’s Pre-Intervention Immune Response Question
A detailed answer for this question would include reference to five aspects of cellular response, which occur sequentially:

1. The cancer cell would exhibit incorrect protein markers for self.
2. T cell receptors would recognize incorrect markers on a cancer cell.
3. This recognition causes T cells to signal for Tc cells to proliferate and form clones.
4. Tc clone cells would recognize cancer cells and release perforin.
5. Perforin lyses the infected cells.

Anne's post-intervention question is shown in Figure 4.2.

*The cold and flu season seems to have been particularly bad this year.*

*Describe the details of the process whereby the immune system detects and destroys flu viruses.*

Figure 4.2. Anne's Post-Intervention Immune Response Question

This question requires an answer that explains a humoral response, and possibly a cellular response if the virus had attacked and entered cells in the body. A well-constructed answer relating to the humoral response would include reference to the following points, representing an ordered sequence of events:

1. Macrophages take up the virus by phagocytosis and break it up into fragments.
2. Fragments of the viral (antigen) are bound with class II MHC proteins and displayed on the surface of the macrophage.
3. A T\text{H} cell receptor recognizes the antigen/protein as foreign, and is activated by binding to the MHC/antigen complex. This leads to its releasing cytokines.
4. Cytokines stimulate proliferation of TH cells which form clones. All have receptors for the processed antigen that is bound to MHC protein.

5. The released cytokines also activate B cells.

6. B cells which have previously taken in antigens present fragments of the antigen, bound to class II MHC proteins, on their surface to helper T cells.

7. In response to B cells' presentation, helper T cells send out chemical signals (more cytokines) to activate B cell proliferation.

8. B cells proliferate and differentiate into antibody-secreting plasma cells and memory B cells which are specific for this antigen.

If the students considered the possibility that the virus had entered cells, their answer should refer to the cellular response and a well-constructed answer would include reference to the following points, appearing in a defined sequence:

1. The virus infects a cell. Viral protein is broken down and displayed with MHC class I proteins on the cell surface.

2. T cell receptors recognize processed antigen markers on infected cells.

3. This recognition of a foreign antigen-MHC complex causes the T cells to signal for Tc cells to form clones.

4. The Tc clone cells recognize infected cells and release perforin.

5. Perforin lyses the infected cells.

Using the points indicated above as a guideline, I blind coded students' responses to the pre- and post-intervention questions for an indicator of conceptual understanding. The indicator was sequence comprehension; that is, knowledge of the sequence of events taking place during the immune response process. I chose this indicator because recognition of the relationships among events is central to the understanding of complex biological systems and concepts. Students'
answers were assigned coding values based on the number of correctly ordered events they described. Students' answers that contained two steps in the correct order were assigned a value of one, those containing three steps were assigned a value of two etc.

Table 4.2. Number of Ordered Events in Immune Response Explanations

<table>
<thead>
<tr>
<th>Number of Events</th>
<th>0</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>&gt;4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sequence Comprehension Coding Value *</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

*minimum of two steps needed to show a relationship.

In the following sample student answer I illustrate an application of the sequence comprehension coding procedure. Each event in the immune response is underlined:

_Cancer cells either lack certain protein markers, or have the wrong ones. Cells called macrophages are able to detect the absent or incorrect markers and eat the cell. The incorrect markers are broken down into an antigen within the macrophage and exposed for T cells to examine. The T cells develop receptors for the antigen. If the cancer reproduced, they will have those same markers, and the T cells will detect them. The T cells will then release a protein which destroys the cancer cell's membrane_ (Paul, post-intervention, March, 2003).

Paul’s answer was assigned a sequence comprehension coding value of 4 for including more than four sequenced events

*Analysis of students’ responses to halogen questions.*

As mentioned previously Steven designed two questions to assess his students’ understanding following the analogy exercise. These questions were part of his final exam (see Figure 4.3).
1. (a) Which of the following reactions would occur (if either)? (1 mark)

(i) \( \text{Br}_2 + 2 \text{Cl}^- \rightarrow 2 \text{Br}^- + \text{Cl}_2 \)

(ii) \( \text{F}_2 + 2 \text{I}^- \rightarrow 2 \text{F}^- + \text{I}_2 \) [Correct answer = (ii)]

(b) Explain your choice. (3 marks)

2. Explain the trend in electron affinity for the second row elements \( \text{Li} \rightarrow \text{Ne} \). (5 marks)

Figure 4.3. Steven’s Exam Questions on the Halogen Oxidation Concept and Electron Affinity

Steven’s second question was not directly related to the halogen topic, but he included this question to investigate if students could “apply” their knowledge of interactions between the nucleus and electrons, gained from the halogen topic, to a new situation, the electron affinity topic.

Steven graded his exams and then we worked together to develop a coding system that would permit a more detailed evaluation of students’ understanding of halogen reactions. Using a five point system Steven and I coded Question 1(b) for indicators of conceptual understanding. The indicators we looked for were meaningful reference to:

1. Effective nuclear charge
2. Attraction between the nucleus and electrons.
3. The relationship between atomic radius and attraction between the nucleus and outer electrons.
4. Relative ability of fluorine and iodine to attract electrons.
5. The transfer of electrons during the oxidation reaction.

Steven and I carried out our blind coding of student responses independently, with an inter-rater reliability of 90%. During the coding procedure, neither of us was aware of which analogy each
student had experienced. An illustration of the application of the coding procedure is shown with reference to the following student response:

*The effective nuclear charge for Br and Cl is the same +7, but Cl is a smaller atom than Br, therefore holds on to its electrons more than Br. The second reaction takes place: F is much smaller than I and holds its electrons more closely than I. The I is much bigger than F. Its electrons are further away from the nucleus and therefore doesn’t hold its electrons as strong as the atom of F.*

This answer was assigned a coding value of 4 out of 5 possible points for including meaningful reference to:

1. Effective nuclear charge: *The effective nuclear charge for Br and Cl is the same +7.*
2. Atomic radius of the halogens: *The I is much bigger than F.*
3. The attraction nucleus and electron: *It’s electrons are further away from the nucleus and therefore doesn’t hold its electrons as strong as the atom of F.*
4. The relative abilities of F and I to attract electrons: *Cl . . . therefore holds on to its electrons more than Br.*

The coding procedures for Question 2 were identical to those used for Question 1. Every written response was coded using a five point system with each point corresponding to a positive indicator of conceptual understanding. These indicators were meaningful reference by the student to:

1. The relationship between effective nuclear charge and position of the elements in the periodic table.
2. The relationship between effective nuclear charge and the radius of atoms.
3. The relationship between effective nuclear charge and the attraction between the nucleus and outer shell electrons.
4. The relationship between atomic radius and the attraction between the nucleus and outer shell electrons.

5. The relationship between the inability of Ne to attract an electron and its low effective nuclear charge or the relationship between the inability of Ne to attract an electron and the presence of a filled outer shell of electrons.

Our independent coding of student responses for Question 2 had an inter-rater reliability of 90%.

Comparing Chemistry Students’ Performance Across Sections

To permit comparison of student performance on the halogen questions across the experimental and comparison sections, I divided the quantitative data from all sections, into four groupings. Each grouping represented the work of students at a different achievement level. Achievement levels were determined based on a calculated average of students’ mid-term test percentage in the chemistry course and their final exam percentage, and were assigned after completion of the course. Students assigned to the group designated as ‘Achievement Level I’ had an average midterm test plus final exam mark of below 50%, corresponding to “no credit” or a low “pass” grade. Students assigned to group ‘Achievement Level II’ had average marks of 50 to 65% (high pass or C grade). Students in group ‘Achievement Level III’ had average marks of 65 to 80% (corresponding to grades of C+ to A-), and students identified in group ‘Achievement Level IV’ had average marks of 80 to 100% (A or A+).

For the analysis, I combined data from students assigned to Achievement Levels I and II to provide a picture of the performance of lower-achieving students. To provide a picture of the performance of higher-achieving students I combined data from students designated at Achievement Levels III and IV. Data from students assigned to Achievement Levels I and II were compared across the experimental and comparison sections. Similar comparisons were
made for data from students assigned to Achievement Levels III and IV. A two-tailed independent $t$-test analysis (Palys, 1997), was carried out on all numerical data, to determine whether there were any statistically significant differences between the performances of students of different achievement levels, in the comparison and experimental groups (Spier-Dance, Mayer-Smith, Dance & Khan, 2005).

**Data Validity**

Researchers working with qualitative data address the question of internal validity – or how closely the research findings are congruent with reality – by using the processes of member checking, triangulation, asking peers for comments on emergent findings and clarifying researcher biases and assumptions (Merriam, 1998). Member checking is concerned with assessing the quality of data and validity of interpretations by discussing them with the research participants who contributed to the data. Triangulation involves a comparison of data collected from different sources. Such a comparison allows the researcher to check for consistency in interpretation and determine if biases or weaknesses are evident. Triangulation and member checking allow the reader to consider whether the results of the research are consistent with the data collected, and thus to assess the reliability of a study (Lincoln & Guba, 1985).

For my study I triangulated interview data from students and their instructors with data from classroom observations, as shown in Figure 4.4.
I used triangulation for cross-validation (Lincoln & Guba, 1985; Merriam, 1998), to enhance the internal validity of my data, to reduce the likelihood of misinterpretation, to confirm emerging themes and reveal any inconsistencies in the data. I also used member checks (Merriam, 1998) during the data collection and data analysis stages of this study to enhance the validity of the data and my interpretations. I did this by requesting feedback from participants on their interview transcripts and on my recorded observations of the classroom, and by asking participants during interviews to explain the significance and meaning of activities I observed in the classroom. The combined processes of triangulation and member checking helped me to clarify meaning and confirm that my observations and interpretations agreed with those of the participants.

Students’ responses to pre- and post-invention questions were subjected to statistical analysis. Means, Chi-square and paired T-tests were performed on this data using SPSS statistical software. Where possible the quantitative data were triangulated with the interview and observational data.
Limitations of Data Analysis

In my role as researcher, I was responsible for data collection and analysis. I decided what was important, what should or should not have been considered when collecting and analyzing data, and what categories were used to organize my data. These decisions are intimately related to my personal beliefs, and prior experiences. Thus my research findings should be considered as individualistic and socially constructed knowledge. In my research and writing of this dissertation, I have tried to represent the reality of the undergraduate science classroom, but this reality is ever changing. As Lincoln and Guba (1985) note, reality is "a multiple set of mental constructions . . . made by humans; their constructions are on their minds, and they are, in the main, accessible to the humans who make them" (p. 295). There is therefore no single reality, waiting to be revealed, and my representation of reality is itself a construction.

Epistemological considerations

As I engaged in this study, I struggled with a number of issues relating to how I would present and situate the findings from my research. In my previous work as a scientist I had accepted the positivist perspective that knowledge is fact-based, and independent of the individual researcher. But during my doctoral studies I came to recognize that learning takes place when an understanding of facts is constructed by the individual in a social context (Davis, Sumara & Luce-Kapler, 2000). In adopting this social constructivist perspective, I accepted that the roles of observer/researcher and observed/research participant are intimately related and inter-dependent, as the researcher is part of the social fabric of the research. Thus, every interview, classroom activity and the writing of this thesis was and is affected by my involvement. As noted by Merriam (1998):
The interdependency between the observer and the observed may bring about changes in both parties' behaviors. The question then is not whether the process of observing affects what is observed but how the researcher can identify those effects, and account for them in interpreting the data. (p.103)

Given that my role as researcher was influential, it was important for me to try to identify and take into consideration this influence when interpreting my data. For example, I had to question whether my other role as a science instructor at this institution could cause students to treat me differently, and be less willing to make negative comments about the intervention. Most students appeared to speak openly during interviews and discussed both positive and negative aspects of their learning experience at the university-college. I interpreted this openness as an indication they viewed me more as a researcher than an instructor. This separation of my role of researcher from that of instructor may have resulted from the fact that only one of the students I interviewed had previously enrolled in a class that I had instructed.

Despite this apparent recognition and acceptance of my role as researcher, I am still aware that students' interactions with me may have been influenced by other factors. For example, were students' attitudes and actions affected by the use of an instructor's office for interviews? Did my age, gender and appearance influence how they responded during interviews? I cannot objectively answer these questions. Merriam (1998) notes that qualitative researchers influence classroom and interview interactions, as well as the design and progress of the study. It is therefore impossible for the researcher to distance herself completely from the study. Still, she should critically reflect on her beliefs, values, historical context and prejudices, and consider how they may influence the research (Denzin & Lincoln, 1998; Merriam, 1998). While I tried to do this, I acknowledge that this reflection remains problematic, because I may hold biases that are not apparent to me, but will affect my interpretations.
Ethical considerations.

The relationships between researcher and participants are central to a case study, but these relationships can be a source of ethical concerns. These concerns relate primarily to my interactions with the instructors and students in my study. When I included these participants in my research, I used an ethics form to outline the guidelines for their involvement, and thus all participants are ensured of anonymity (see Appendix G). There are, however, other ethical concerns that I could not address with such a form. I consider the concerns relating to instructors and students separately.

During my study, I observed and interviewed three instructors, who are also colleagues at the university-college where I am employed. The dual nature of my role prompts a question – am I breaching a trust if, in my interpretation of data relating to the instructors, my findings are critical of their activities? Such situations can arise because instructors often espouse pedagogic beliefs that are not supported by their classroom activities. For example, Murray and MacDonald (1997) have shown that many instructors view their approaches as student-centered, while these approaches are actually teacher-centered. This concern is accentuated by the fact that anonymity is not a cloak of invisibility for an instructor, who may believe that a reader could recognize them. My response to this problem is pragmatic. I do not include any information, such as interview quotes or observations, which would allow the instructor to be identified, but I do include any data which is relevant to my findings and true to the object of the study.

For students, the use of pseudonyms, coupled with the large numbers of students involved in my research, provides a degree of anonymity. However, there is an ethical question that relates to students’ comments about instructors. Some students commented critically on the actions of instructors, leaving me with an ethical dilemma. I have a responsibility to these students to represent their views, but I also have a responsibility towards the instructors involved.
My solution was to include both positive and negative comments, but not to attribute them to a particular instructor or course.

**Reflections on my Role as Researcher/Participant/Observer**

Prior to becoming a graduate student, I was a full-time chemistry and forensic science instructor at the university-college where my research was being carried out. While conducting my research, I continued to teach part-time at the same institution. I was therefore concerned about my role as classroom researcher, and the issues that related to my being both an “insider” and an “outsider.” I played multiple roles as researcher, instructor, participant, observer and colleague and it was often impossible to separate my outsider/researcher role from my other roles (Davis, Sumara & Luce-Kapler, 2000). This complex overlapping of roles inevitably affected, and was affected by, many aspects of my research. Finding a balance between these roles was difficult. For example, in my new role as graduate student-researcher-participant-observer I tried at first to be an observer, not a participant, by distancing myself from my other role as instructor-colleague. As I sat as an observer (outsider) in the back of a colleague’s classroom, I believed I could merge into the background. However, I was reminded that I was still seen as an instructor (insider) when one student informed me that they had really enjoyed activities in my class the year before. This episode made it clear that my presence in the classroom influenced, and was influenced by, the way in which the study was conducted. Patton (1990) summarizes the balance between being an outsider/insider that is required by the researcher who is doing qualitative research:

Experiencing the program as an insider is what necessitates the participant part of participant observation. At the same time, however, there is clearly an observer
side to this process. The challenge is to combine participation and observation so as to become capable of understanding the program as an insider while describing the program for outsiders. (p. 207)

To present my research and findings convincingly to the reader, I recognized that I needed to recreate the actions, perspectives, experiences and meanings that could validate my naturalistic case study (Eisner & Peshkin, 1990). This required including rich descriptions that would allow the reader to experience a situation in which they could not directly participate. To assist the reader in understanding my research space, I created a series of vignettes that are representations of situations that developed during the analogy activities. These vignettes are intended to provide the reader with a sense of the complex and continually changing nature of my interactions with the other actors/participants – the instructors, the students, the classroom situation – during the analogy-generating process. Recalling the interplay of events taking place at different times and places seemed reminiscent of a drama production, where the actors and scenery change from one scene to the next. I therefore decided to present my vignettes about analogy development as scenes in a play.
In this chapter, I present a series of vignettes to take the reader through the steps involved in one cycle of the analogy activity, while showing how the various steps in the process are related. A vignette can be described as “a picture or description of a situation . . . (that) can help capture the essence of a classroom situation” (Veal, 2002, p. 1). My intention is to provide rich descriptions that can simulate the reality of the classroom, and help the reader gain insight into my research. In presenting these vignettes from a personal perspective, I try to highlight the complexity of a process that involves, and is changed by, the interactions of a number of participants.

Awareness of my own multi-faceted role, coupled with the complex and continually changing nature of my interactions with other actors – my colleagues, instructors, students and many others – leads me to recognize the confluence of subjectivity and objectivity that must occur during this research. To illustrate events, situations and my role in bringing student-generated analogies into the science classroom I present the vignettes as scenes and events in a play, in which I am, at different times, a director, a performer, a spectator and a critic. A dynamic flux exists between these roles, which in turn provides new insights into my roles. My shifting roles, combined with the inputs of other players – my colleagues, the teachers, the students, and the science itself, produce a complex fusion of the scripted/expected with the unscripted/unexpected.
The Programme

Prologue: Planning the analogy

Meeting the Cast: I meet with Anne’s class to explain the study

ACT I

Scene one: Anne’s biology lecture
Scene two: Steven’s chemistry lecture

ACT II

Scene one: Rehearsals: student’s plan their analogies
Scene two: The Performance: student biology group one
Scene three: The Performance: student biology group two
Scene four: The Performance: student biology group three
Scene five: The Performance: student chemistry group four

ACT III

Scene one: Discussion & critique following the performance

Epilogue: My reflections

Figure 5.1. The Programme
Prologue: Planning the analogy

Place: Anne’s office.

Time: Early August

I am in my office, waiting to meet with Anne to discuss the possibility of introducing student-generated and performed analogies into her first year biology majors class. This is the most relaxed time of the year – it is three weeks before classes, and I have all my photocopying, book orders and preparation completed, ready for the new semester. I walk the few steps to Anne’s office, and we spend a few minutes talking about our summer. How is the garden? Have the dahlias survived the slugs? I think we both enjoy these few minutes before getting down to business. When I talk to male colleagues we rarely mention life outside the college, but with female colleagues, it is somehow easier to move between the worlds of work and home, which cannot really be separated. I lead the conversation towards my research, and explain what I want to do, and why I am interested in it. I have previously used student-performed analogies in my classes, where student volunteers acted out various roles. I was impressed with the interest shown by the students, and the understanding that they exhibited when answering test questions. It gave me that rush you get when you try something new – and it works! Now I want to push the barriers a bit further, because I am aware that the analogies we acted out were my analogies, not the students’. Will it be better for students to construct their understanding, from their own analogies, rather than relying on mine? I know what constructivist perspectives tell me about learning, but it is time for me to find out whether all the theory really works for students and me. I think it is a bit like understanding death. When you are a child, death is not real, and it is only when someone close to you is gone – forever – that the theory of death becomes grounded in reality. Now I need to ground the theory of education in the reality of the classroom.
I know that Anne has recently completed her doctorate in Science Education and uses a number of different learning strategies in her classroom. That helps, because she will be able to see the relationship between using this student-centered strategy and educational theory, and is enthusiastic about trying something out with her first-year biology class. It's no coincidence that I have chosen Anne for my first trial-run – I need her support and ideas as I work in an area where I don't know the answers, and think I may also be missing some of the questions. All last night I was worrying about the what-ifs – what if she isn't interested, what if she doesn't have enough time - and now I am so happy we are at least going to start something. We arrange a time-line for the study involving her class, and she suggests a topic – the immune response. Anne picks up a felt pen and spontaneously starts writing on the white board:

*Probe question and self write ..... 15 minutes*
*Group planning, props and rehearsal ..... 45 minutes*
*Acting ..... 20 minutes*
*Discussion/evaluation ..... 10 minutes*

“How does that sound?” Anne asks. “Great,” I reply, happy that Anne is willing to devote an hour and a half of her class time for the students to generate and perform analogies. Anne continues, “We could use 6 groups of 7 people or 5 groups of 8 people and designate one person in each group as a recorder. The immune response is quite complex, so they will need fairly large groups.” Anne hands me a copy of a diagram, saying, “This is the diagram of the immune response that I will be giving them, and I will be asking them to read about the immune response in their textbooks.” I stare at the diagram she just handed me and it appears as a jumble of arrows, images and labels that I don’t immediately recognize. Could the immune response have
become that much more complex since I learned it at university? It is apparent that I had better do some biology homework, if I want to understand the analogies that students are going to produce, and relationships of those analogies to the science concept. I am aware that my role is changing, because I’m so used to being the dispenser of information and help to my students, yet here I am, feeling like a novice first-year student when I ask, “Can I borrow the text and any other hand-out materials to read around the subject?” Anne pulls a thick text off her overloaded bookshelf, bookmarks a chapter and hands me the book. I think to myself that chemistry isn’t the only area where first year textbooks contain too much information. I look at the textbook and read:

The helper T cell itself is also subject to regulation by cytokines. As a macrophage phagocytoses and presents antigen, the macrophage is stimulated to secrete a cytokine called interleukin-1 (IL-1). IL-1, in combination with the presented antigen, is what activates the helper T cell to produce IL-2 and other cytokines. Also, in an example of positive feedback, IL-2 secreted by the helper T cell stimulates that same cell to proliferate more rapidly and to become an even more active cytokine producer. In these ways, helper T cells modulate both humoral (B cell) and cell-mediated (cytotoxic T cell) immune responses. (Campbell, 2002, p. 909)

I wonder what exactly are helper T cells, cytokines, interleukin 1 and 2 and B cells, and how does the humoral response differ from the cell-mediated response? Can the language of science be so complex? The language of chemistry seems so easy compared to that of biology. Then it occurs to me that the language of chemistry is only easy for chemists – beginning chemistry
students must feel exactly the same trepidation and confusion that I am feeling now. Despite the knowledge that I need to update my biology, I leave Anne’s office feeling exhilarated. At least I have made a start, even if I am not sure where my research will be taking me.

Meeting the Cast

Place: Anne’s biology Classroom.

Time: Early September.

Setting the scene: It is about a month since Anne and I first met to discuss the analogy activity. Now it’s time to meet Anne’s biology class to explain my study and to hand out ethics forms. It is the beginning of the period, and Anne, a tall, dark haired, middle-aged woman with a confident air and voice is standing at the front of the class, while I am standing behind to her right. Anne extends her hand towards me and announces in a warm, welcoming tone:

I would like you all to meet Lesley Spier. She is here to tell you about her research at UBC involving analogies, and to invite you to participate. I will be asking you all to generate your own analogies later in the semester when we cover the immune response and Lesley is interested in studying this and interviewing some of you.

Anne’s obvious interest in my study creates an air of enthusiasm and interest, which is transmitted to, and reflected by, the class. I thank Anne and explain to the students what my study involves, what I mean by the term analogy and why I believe that student-generated and performed analogies can be a useful heuristic for learning science (except I do not use the term heuristic!). I hold up a large diagram (which I had previously distributed to the class) showing the
cone of learning (Dale, 2002) and point out the importance of the learner’s active physical involvement in learning. I also give the students some guidance on the generation of analogies, following the approach described by Wong (1993) and described earlier in chapter 4. Some of the important points that I emphasize include taking time to engage with the scientific phenomenon, generating an analogy by relating it to an area of knowledge that is familiar to them, evaluating it with respect to how closely the analogy relates to the target concept and modifying it as necessary.

So that the students will understand their role in the study, I then briefly outline the methods that we will be using. I explain that, as part of her class, Anne will be giving them a take-home work-sheet and will ask them to devise their own personal analogies that represent a particular science concept. Following this, Anne will be asking them to discuss their analogies in groups, and during this time they will have to agree on one analogy that best represents the phenomenon in question, and can be performed to the class. The groups will also decide if any further development of the analogy will be required and whether there are any props they might want to use. I mention that I will bring some props to class, but they can also bring their own. I explain that I am asking their permission to videotape the analogy performances, to use their work related to analogies and the immune concept, and that I will be seeking 10 people to volunteer to participate in interviews. I also explain the confidential nature of the study. Finally, I mention that students will be encouraged to comment on aspects of the generation and presentation of the analogy, and on how closely each group’s analogy represented the science concept. I then give a more detailed explanation of the ethics form and hand this out to the students, giving them instructions to return their form the following week.

I am concerned that students will not want to be on a video, and emphasize that their participation in this is voluntary. Up to this point, everyone has been very attentive and serious,
but now, as I am talking, I become aware that I am the only one who has spoken during the last ten minutes. The students all appear comfortable with this situation – this is what they are used to; it is what they expect, and they are quite willing to allow me to dispense information to them. I suggest to the class that if they want to remain anonymous on the video, they can use paper bags over their heads. My suggestion produces a great deal of laughter. I am pleased to get a response from them – perhaps it has given me some sort of connection with these strangers. I stay behind to answer a few questions such as “Can we bring our own props?” “Can I take part in class without doing the interview?” “What kind of analogies should I do?” I begin to realize that these science students expect me to tell them exactly what I expect them to do in the analogy exercise, and I am probably pushing some of them outside their comfort zone. Some of them are definitely disappointed that I do not have all the answers to their questions. I ask myself how this is going to work – it is definitely different to the ritual of the science lecture, where everyone knows his or her part, and the script is carefully followed. We will just have to wait and see.

ACT I, scene one

Anne’s biology lecture

Place: Back in Anne’s biology classroom.

Time: One week later in September.

“She whistled for her dog Spot.” Anne’s statement, spoken quietly, catches every one’s interest. It seems to be an odd way to start a biology lecture, but then she asks, “In order for someone to whistle, what kind of things would have to be involved?” A student near the front says, “Exhaling”, another to the side says, “Voice box.” Anne prompts, “In order to exhale what is going to be involved?” A student to the left answers, “The diaphragm,” another student responds with, “Muscles.” Anne probes further, apparently to seek another term she wants to
hear, "If your muscles control exhalation what is also going to be involved? What controls them? What controls any of it?" "Respiratory control centre" is the subdued reply, to which Anne responds:

*Good*, the respiratory control centre is involved in sending impulses. What else has to be involved to form your mouth, to make the sound that Spot comes to?

We’ve talked about muscles and the respiratory control centre, so what else is involved? Where do the instructions to do all that come from?

One of the more vocal male students at the front again responds with "Memory". Another suggests that the limbic system must be involved. Anne is busy writing down these responses with a black felt pen on the overhead projector at the front of the room. She continues “So alright, we have memory and the limbic system, so what else is involved in terms of the flow of information?” A student, who has not previously spoken, responds, “The brain has to be involved as well, the motor cortex”, Anne replies, “Yes, all those things must be involved. I guess if you can, order them in some way, try and localize what is going on.” After a few moments of silence, Anne explains the order and the process of respiration in more detail to the class. I am sitting in the far back corner of the class, making notes like everyone else and enjoying this opportunity of seeing how another instructor organizes her class. Suddenly it occurs to me that respiration wasn’t the topic I had discussed with Anne! Have I got the dates muddled, because I thought that Anne was going to teach the immune response today?

Anne continues with her detailed explanation of respiration, interspersed with questions and answers. She busily writes notes on the overhead transparencies, just as I have done many times previously. Now students begin copying the notes more frantically, and seldom speak.
Then, Anne stops writing, looks up and announces “The next topic is immunity: the humoral and cellular responses. Before I forget, does everyone have a copy of this (holding up a diagram) the humoral and cellular response?” I am relieved that I am in the right class after all. Forty minutes have gone by and the class appears to be losing some of its vitality and interest. Students at the back are writing each other messages and looking around. Two female students sitting nearby look across at me, and look guilty when they realize that I have seen their doodles and notes being passed to each other. I reflect that, for these first year students, college is much like high school. I notice how students at the front seem to be trying to remain focused. Anne interrupts my thoughts when she asks, “How does the body distinguish between self and non-self?” A student at the front replies that MHC proteins are important. Anne agrees and proceeds to explain how macrophages check for foreign cells and destroy them. She refers to a figure on a handout sheet and continues to explain it in some depth; I recognize the handout as the one that she gave me some weeks earlier. Anne continues, relating the subject matter (MHC proteins), to heart transplants and tissue rejection, and then to cancer cells. This topic is apparently stimulating, and recaptures the students’ interest, bringing the class back to life. Soon, Anne says, “Thursday is the quiz, so read the section in the book before coming to the next class and remember to fill in the modeling sheet and bring it with you.”

I fold up my notebook and unplug my tape recorder. One girl with long red hair approaches and asks, “Is this going to be a bit like we did in your class? I really enjoyed acting out the mass-spectrometer, and I still remember it” I reply that I am pleased to hear that she still remembers what we did previously, but that this will be a bit different, as it will involve student-generated and performed analogies, rather then a teacher-generated role-play, as we did before. She smiles and comments that she is looking forward to the activity. I turn around and find that
the room is almost empty; everyone has left except two students who are making their way towards the door. It must be time for the next class.

ACT I, scene two

Steven’s chemistry lecture

Place: Steven’s chemistry classroom.

Time: One week later in September.

Steven sits down on the front student desk to the right of the classroom, facing the class. The class is relaxed, with students still entering and social conversations taking place. Two students approach him with questions, which he spends a couple of minutes answering. They return to their seats and Steven begins to talk. “Today we are going to talk about the effect of changes in pressure, volume and temperature on gases. Can anyone remember what we said last week about the particles making up gases?” I am amused by his choice of the word “we”. I expect that really means “I”. There are mutterings, and then an older student at the back speaks. “The particles are in continuous random motion, moving round and bumping into each other” Steven replies, “Yes, that’s right, at room temperature. So what do you think will happen if the gas is heated up?” A male voice to the right answers, “They will speed up”. Steven acknowledges that this is correct and proceeds with another question “What would happen to the number of collisions of the particles with the walls of the container?” A female student to the left starts to say, “Wouldn’t they remain the same . . . ?” but the older male student at the back of the room interrupts and announces loudly, “No, they would have to increase.” Steven walks towards the blackboard and starts drawing a box with dots and arrows representing gas molecules bouncing off the sides of the container. He explains (referring to his diagram) how, if the gas is heated and the container remains the same size, the faster-moving particles would collide more
frequently with the sides of the container creating an increase in pressure. He follows this by giving the following analogy:

If you are at a dance where people are drinking, the more the people drink, the more energetic they get and they dance more wildly and are more likely to bump into other people. The difference between drunken dancers and molecules is that when drunken dancers fall down they sometimes stay down; whereas gas molecules just keep going and going. So perhaps it would be better if we thought about drunken energizer bunnies dancing.

The class fills with laughter. Apparently, drinking and dancing are things that these college students can relate to!

**ACT II, scene one**

**Rehearsals**

Place: Back in Anne’s biology classroom.

Time: One week later in September.

As I walk along the hallway towards Anne’s classroom, a small group of laughing students are quietly exiting in the opposite direction, occasionally checking over their shoulders, like school kids playing hooky on a sunny day. Apparently, not everyone in the class is willing to participate in the analogy exercise. These are the ones that got away, both figuratively and in reality. As I enter, Anne is already standing at the front, instructing the students to try a practice test question on the immune response, without the aid of their textbooks. Over the next few minutes, some students are working diligently, while others sigh and seem at a loss as to what to
write. I know that these test questions are not for marks, which might be why the class still seems relaxed and friendly. While they are working, I attempt to mount the video cameras on the tripod and to unobtrusively set up the tape recorder in the back corner of the class. I place the large silver microphone on the desk and camouflage it with my coat, in an attempt to make the students feel more at ease. Anne and I empty the bags of props I brought to class on a desk in one corner of the room, and an assortment of multi-colored balloons, straws, scarves, pens, colored paper and sticky bows falls out. Students are handing in their practice test questions to Anne. When all the students have finished their questions Anne tells the class that they will now be developing their analogies, and suggests that they work in their usual groups. She recommends that one person should act as the recorder of the group’s ideas while they discuss which idea they will act out, and gives them my handout sheet on which they can record their ideas and comments. There is a sudden buzz of activity, as excited students gather and rearrange their chairs to form groups, ready to discuss what they might do. One student reveals a water pistol hidden in his jacket pocket. At least someone has spent time thinking about the exercise! Members of the “water-pistol” group don bandanas and move out into the hallway to practice. I can hear shouts of laughter spreading across the hallways, even passers-by are smiling, and a small audience seems to be gathering in the hall outside the classroom. Meanwhile inside the room, one group of female students is running around with an array of pink and white balloons attached by clothes pegs to various parts of their clothing, and with their hair containing an assortment of colored straws. I am amused to think that these students, who usually seem to be bound to their chairs and tables by some invisible classroom force, are laughing and running round the room. It’s party time! At last, they are not requiring Anne or me to control the class. The balloon group joins the bandana group to practice their modeling in the hallway.
Of the two groups left in the room, one is busy making signs on colored cards, while the other group seems to be making two-tone wristbands and blowing up balloons. These groups soon leave to practice in the hall with the others, adding to the mounting noise level. The hallway seems to have taken on the role of the kitchen during a party – people just seem to prefer to congregate there. Is it that the students subconsciously view the classroom as a place to sit and be taught, while the corridor is a place to talk with friends?

After approximately forty-five minutes of planning and rehearsing, it’s time for the groups to give their presentations. Two groups request to go first, so Anne announces that she will decide the order of presentations by drawing lots. Before the performance starts, I ask for volunteers, to help operate the video cameras while their group is not presenting. I thought that if the students saw one of their peers operating the cameras they would feel less intimidated, rather than having a stranger like me standing in front of them. Two students eagerly step forward to help, they obviously feel more comfortable with video equipment than I do. I am not surprised that the volunteers are both males!

Anne takes her seat at the back of the room and I sit behind her. The ‘set’ is an open space at the front of the room, surrounded by an assortment of tables and chairs with a large black board as a backdrop. We are just about to start the analogy performances when Karen, the head of the biology department, walks in. Anne turns round to me and hurriedly explains that she had thought Karen would enjoy watching the performance. I am concerned that another visitor (especially the department head) might make the students very nervous, but they seem to accept Karen’s presence readily, and I wonder if she has been invited into Anne’s classes before. While it seems that the students probably do not share my concerns, I nevertheless begin to feel tense, and hope that the performances will go well and remain on topic, particularly now that we have a visitor.
ACT II, scene two

The performance: Student biology group number one

Place: Anne’s biology classroom.

Time: Immediately after the in-class preparation.

“Are you ready to roll? Then, ACTION!” Anne announces.

Narrator, standing to one side of the stage: “It is another quiet day in Immunity city, but little known to the population is an evil villain”.

(The evil villain enters, with a large letter ‘A’ written on yellow paper pinned to his shirt.

Written underneath are the words ANTI-GEN or “Auntie Jen”).

Anti-gen: “I’m Anti-gen”.

Narrator: “Responding to his evil is our hero the real Mac-Phagy”. (A macrophage)

Mac-Phagy enters. On his shirt is a green sheet of paper with his name, followed by a large letter ‘M’.

Mac-Phagy: “Hello who are you?” (Mc-Phagy asks antigen).

Anti-gen: “I’m Anti-gen” (is the stilted response).

Mac-Phagy: “Nice to meet you” (replies Mac-Phagy).

Mac-Phagy proceeds to wrap Anti-gen up with a large piece of tape immobilizing Anti-gen’s arms.

Narrator: “Mac-Phagy engulfs Anti-gen by phagocytosis”.

A whistling noise is emitted by Anti-gen.

Mac-Phagy: “What’s that?”

Anti-gen produces a colored scarf and gives it to Mac-Phagy.

Anti-gen: “It’s a fragment”.

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Narrator: “Just then, Mr. T Cell walks by”. (The T cell actor is easily recognizable by having his name on a blue sheet of paper on his chest).

Mr. T Cell: “I recognize that.” (The colored scarf held by Mac-Phagy i.e. processed antigen).

“Hmm, I feel the need to proliferate.” (Mr. T Cell gives T Cell labels to 2 students, who hold them up for the class to see).

Narrator: “Mr. T Cell clones are made. Suddenly because Anti-gen has now become super powerful, after being engulfed by Mac-Phagy’s super endocytosis capabilities, Mr. T Cell and the T squad are called in. The T squad then causes serious damage”.

As the narrator describes the antigen as being super powerful Mr T Cell grimaces and puts his hands over his face. He has noticed the narrator’s error in saying that the antigen has become super powerful rather than less powerful.

Mr. T Cell: “I have run out of immobilizing tape and will have to resort to towel whipping what’s left of Anti-gen”.

Narrator: “After giving Anti-gen the thrashing of his life the T cells cause endocytosis of what is left and Immunity City is saved”.

The performance is inter-dispersed by laughter from the audience including the department head and, as it ends, a loud burst of applause fills the room. I am pleased that the performance has been a success in terms of its entertainment value; I hope that it is as successful for learning the immune response.

On reflection, I am amazed that this group came up with a cartoon story analogy and managed to act it out so well. Some of the main characters seem to be very confident and comfortable with acting and the use of a narrator helped me to understand their depiction of the science concept. I subsequently learn during interviews that one of the main actors has previously taken theatre courses and relished the chance to act in the analogy activity, rather than
as he put it ‘sitting for 8 hours in science classes all day taking notes.’ I eagerly await the next performance.

**ACT II, scene three**

**The performance: Student biology group number two**

Place: Anne’s biology classroom.

Time: Immediately following group one.

The next group gets up and starts rearranging the tables and chairs to form a cluster of chairs around one table in the front left hand corner of the room. They first announce that their performance is based on a ‘Cops and Robbers’ analogy. The bad guys (invading antigens) are wearing white arm badges and take their places around the table at the front of the room. Their roles become apparent when they ask each other “How many guys did you infect yesterday?” “We’ve been pretty busy,” is the reply. The sheriff (a T cell) approaches, proudly wearing a large star shaped badge and asks “You folks new in town?” “Well, howdy sheriff,” is the reply from the ‘bad guys’. The sheriff asks, “Are you going to be hanging around for a while longer?” “Well what are you going to do about it?” the bad guys ask. “Well if you guys are hanging around I will go and get some backup,” replies the sheriff. Before long, the sheriff is calling for backup (T cells). When the backup arrives with green arm badges they hold up their hands like guns aimed at the ‘bad guys’ and pop balloons at the same time (to the surprise of the audience, who applaud loudly).

I was surprised that instead of just playing the roles of antibodies, antigens, T cells etc., the group was acting out a “Cops and Robbers” type scenario, where the “bad guys were the invading antigens” that were soon to be surrounded by T cells. These students have definitely
related the new concept to a scenario they are familiar with, but I wonder how much their creative role-play will enhance their learning of the biological concept.

ACT II, scene four

The performance: Student biology group number three

Place: Anne's biology classroom.

Time: Immediately following group two.

The third group performs their analogy using a theme of Jurassic Park. The main character obviously relishes his role as the invading velociraptor (*antigen*) and emits strange raptor sounds, jumping on tables. His attack on two people (*representing his infection of tissue cells*) is performed with up-bent arms, held like talons. Another person (*representing a T cell*) fires a stream of water from a water pistol directly at the raptor's face saying loudly "die, die," the raptor then dies an agonizing death. Then, two more people wearing red jackets (*other antigens with protective coating*) enter the scene. Using a long piece of tape, a person who says he is a macrophage strangles one of the jacketed people, who promptly falls to the floor. The remaining person wearing a red jacket is hit in the face by an unexpected jet of water produced from a water pistol held by yet another person (who claims to be a different T cell). The last jacketed person rolls to the floor in excruciating pain and dies.

This analogy performance, partially narrated by the actors themselves, leaves the audience consumed by fits of laughter and applauding warmly. I join in the applause - this performance was definitely entertaining. However, I find this analogy left me wondering how the various parts relate to the science concept. What are the students representing with the water? Is it a chemical messenger, such as perforin, released by T cells to destroy infected cells, or is it intended to be something else? What do the jackets represent? I am guessing they represent
processed antigen bound to MHC protein, but I am not sure. Clearly, this analogy is causing me to think about what is, and is not, being represented, and prompts me to compare it with the science concept in the textbook. I begin to wonder if I learn more about the science concept by seeing a performed analogy that is not completely explained by the performers. I decide that during interviews I must ask students for some detailed explanations of what they are depicting.

ACT II, scene five

The performance: Student chemistry group number one

Place: Steven’s chemistry classroom.

Time: September, one week after my meeting with Steven’s chemistry students.

In Steven’s chemistry class groups are waiting to perform. Steven asks who would like to go first and he gets an immediate response:

‘Raggedy Anne’ sits a little nervously on the front desk, with her red braids draped behind her shoulders, her legs crossed, with a sheet in her hands. She recites her lines, as her fellow performers, balloons in hand, become the molecules in action at the front of the room. She continues:

Here we have a ‘happy’ bunch of hydrogen atoms.

(Pointing to her fellow performers, each of whom is holding a white balloon and moving around at the front of the room).

These atoms have ‘happily’ spread out to fill their container. (I notice that happiness here is interpreted as enthusiasm). They run around bumping into the walls and each other exerting pressure on the walls. This is kinetic energy.

(The performers bump into one another and into the invisible walls surrounding them, moving their balloons at a ‘regular speed’).
But what is this? Their container has shrunk! As the volume decreases, their collisions increase causing more pressure due to a shorter distance to travel between collisions.

(The performers move with their balloons at a 'faster speed' and move in closer to represent a smaller container).

Interestingly enough, if we put a little heat under these happy little atoms we could increase the kinetic energy, increasing their collisions per second and increase the pressure all at once.

(One performer uses a red paper as a flame underneath the balloons and the balloon performers move at a 'much faster speed').

The class applauds. Again, students appreciate being entertained in a novel way. Steven thanks the students for their great performance and asks the next group to get ready to perform their analogy. While I wait for the next group I reflect on the performance I have just witnessed. I am pleased to see that the actors seemed to understand the science concept, and their portrayal was reasonably accurate. However, I am disappointed that the students decided to use a role-play in their analogy presentation. I wonder if this is a function of my directions on producing analogies being unclear, or whether it is due to this being a college preparatory class. Steven had not indicated that he wanted the students to perform role-plays rather than analogies and he seems satisfied with their performances. Perhaps this topic lends itself to a role-play activity, with the students taking on the roles of the molecules themselves. I find myself questioning if it really mattered whether students use a role-play, as long as learning happened.
ACT III, scene one

Discussion & Critique Following the Performance

Place: Steven’s chemistry classroom.

Time: Immediately following the analogy performances.

The audience applauds the final performance, and after a few moments, Steven says how much he enjoyed the performances, and asks the students what they thought about the analogies. I am sitting in the back of the classroom quietly observing and making notes in my journal of the conversations taking place. In response to Steven’s enquiry, a number of students respond:

Audience member #1: All the groups did really well and portrayed the molecules well, some were very amusing, and I liked the one with the transformations from solid to liquid to gas.

Audience member #2: Group 1 did a good job; they showed the balloons bouncing around more when they added heat.

Audience member #3: In group 3 it was hard to visualize movement I couldn’t tell if the people were the molecules or the balloons, as the people stood still.

Steven: I liked the way the particles in the solid were vibrating not stuck together and still. When you are gas molecules, you can head off in all directions and one of you should be over at the pub right now! It is interesting how some of you came up with different views of the same thing. When molecules move around randomly and they move into more space, what happens to their speed?

Audience member #1: It stays the same.
**Steven:** I got the impression from one group that when they moved into a larger space they were moving faster. They will move at the *same* speed but they have more space, so there is more distance between them. I was really impressed; you people did really well. I will show a gases video after the break, to give you another perspective.

I am pleased Steven is able to discuss one groups' alternate conception that he has noticed during their performance without embarrassing or upsetting the students. The students seem eager to hear what Steven has to say, and accept his comments without further questions. I reflect that when I have taught the gases topic I never considered that students' understanding of the topic might be completely different to mine. I wonder if a computer simulation of the movement of gas particles from one container to another would be helpful to students, but then I remember that when I have shown a simulation or a video in my classes students seem to become disengaged very quickly.

After the class discussion, the students gather in small groups in readiness for their break, I hear them talking and laughing about their performances as they exit the room. One student comments to me that although she had been very apprehensive about the whole thing it proved to be a lot of fun. Another student stays to ask Steven about the video, while others quickly return their props and exit the room for a well-deserved break. I collect all my props and cameras and follow suit.
ACT III, epilogue

My reflections

In reflecting on the analogy activities, it appears that, through their involvement, students were able to produce analogies that were both relevant and interesting to them. So often in the undergraduate science classroom, the individual backgrounds of the students have little or no bearing on the content being taught, and the classroom is “owned” by the instructor. The analogy activities seem to have allowed both instructors and students to have a stake in the learning/teaching opportunities that developed.

All of the instructors involved recognized the analogy exercise as a legitimate pedagogical activity. They valued the activity as a means of enhancing a sense of community within the classroom and as a novel and enjoyable approach for promoting student-centered learning. Anne commented that she enjoyed trying new approaches that were student-centered and that she might try something similar herself in future classes. Steven noted that this type of activity seemed well suited for his college-preparatory students, who previously were not always willing to engage in classroom discussions and who became a lot more vocal in class following the activity.

Students appeared to value and appreciate this novel approach to learning science. Many commented on how much they had enjoyed developing and performing their analogies with their peers, and even students who at first felt intimidated by performing in front of their peers later acknowledged that they enjoyed the activity. For the students, it seems the activity had brought the science alive, making it both memorable and relevant. A number of students used the
occasion to learn from other students in their group, or to clarify their understanding of the science by asking the instructor, or by checking on information in the text.

However, it didn’t seem to be just the classroom activity that brought science alive for the students. The dramatic aspect seemed to be important in prompting students to interact with each other, to question and discuss the science itself. The preset agenda that often exists when we teach science, and the expected roles of instructor as the provider of knowledge and student as the receiver, seemed to be transformed by the activity. As the enactments unfolded, each participant had responded to a series of situations and roles, rather than following a predetermined path defined and limited by the curriculum and the instructional paradigm. Instead of one actor delivering a soliloquy to the audience, everyone had been actors participating, interpreting, improvising and questioning the subject that we call science.
CHAPTER SIX

THE ROLE OF STUDENT-GENERATED ANALOGIES IN PROMOTING CONCEPTUAL UNDERSTANDING

In this chapter, I address my first research question:

_In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?_

To answer this question, I consider whether the use of student-generated and performed analogies produces measurable improvements in conceptual understanding, and if involvement in these activities helps students transfer knowledge gained during the activity to novel problems and situations. I present my research findings by examining two in-depth cases of analogy use, one in a chemistry class and one in a biology class. These two cases provide a comprehensive look at analogy use in the post-secondary setting.

Learning About Oxidation of the Halogens Through Analogies

Four sections of Steven's introductory chemistry course participated in analogy activities. One of these sections (referred to as the experimental section) took part in an analogy-generating exercise. The other three sections (referred to as the comparison sections) were taught via a teacher-generated analogy, as described in chapter 4. A brief description of the analogies designed by students in the experimental section is presented in Table 6.1.

To determine if participation in generating and performing analogies had resulted in measurable conceptual understanding, I examined the students' responses to two final exam questions, one on halogens and a second on electron affinity, both of which were set by Steven.
to assess his students’ understanding of halogen oxidation. The questions as they appeared on the exam are shown in Fig. 6.1. Students in all four sections of Steven’s chemistry course answered these questions, and I analyzed their responses for information on students’ ability to apply the knowledge they had learned.

Table 6.1. Student-Generated Analogies (Oxidation of the Halogens)

<table>
<thead>
<tr>
<th>Analogy theme</th>
<th>Analogy description and details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pirate Ships</td>
<td>Two pirates from competing pirate ships fight a sword-fight. A pirate from one ship has the label ‘F’ and has 7 black balloons attached to their clothing. A pirate from the other ship has the label ‘I’ and 8 black balloons. During the sword fight one pirate kills her opponent, and a pirate labeled ‘oxidizer’ removes a balloon from pirate ‘I’ and gives it to pirate ‘F’ (*representing the transfer of an electron from an iodide ion to a fluorine atom in the reaction: ( F_2 + 2 I^- \rightarrow 2 F^- + I_2 )).</td>
</tr>
<tr>
<td>Beauty Pageant</td>
<td>Group members portray contestants in a beauty pageant, where the more attractive contestant, ‘Flora Fluorine’, is able to more strongly attract boyfriends than the less attractive ‘Ida Iodine’. (<em>The boyfriends represent the electrons that fluorine and iodine would compete for in a reaction such as that indicated above for the pirate analogy).</em></td>
</tr>
<tr>
<td>Cruise Ship</td>
<td>Life rafts leave a sinking cruise ship. In order to accommodate surviving passengers, it becomes necessary to transfer survivors from overcrowded life rafts to those that are less crowded. (<em>The transfer of survivors represents the transfer of electrons in oxidation-reduction reactions to produce an energetically favorable situation).</em></td>
</tr>
</tbody>
</table>
1. (a) Which of the following reactions would occur (if either)? (1 mark)

   (i) \( \text{Br}_2 + 2 \text{Cl}^- \rightarrow 2 \text{Br}^- + \text{Cl}_2 \)

   (ii) \( \text{F}_2 + 2 \text{I}^- \rightarrow 2 \text{F}^- + \text{I}_2 \)  [Correct answer = (ii)]

   (b) Explain your choice. (3 marks)

2. Explain the trend in electron affinity for the second row elements Li \( \rightarrow \) Ne. (5 marks)

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**Student Performance on the Halogen Exam Question**

Steven designed the halogen exam question to provide a direct measure of students’ understanding of the oxidation of halogens. As described previously, students’ answers were first graded by Steven, and then coded by Steven and me. Results of this analysis are displayed by achievement levels in Table 6.2 and Figure 6.2. Coded values calculated at each achievement level in the three comparison classes were combined and used to calculate composite mean values. These mean values were compared with values from the experimental section. In addition, the coded values of students in Achievement Levels I and II were averaged to generate a composite mean for low-achieving students. A similar mean was calculated for the higher-achieving students assigned to Achievement Levels III and IV. A composite mean across all Achievement Levels was also calculated.

The mean value for measures of students’ conceptual understanding for each achievement level was higher in the experimental group than in the comparison group. This difference was statistically significant for students performing at Achievement Levels I, II and IV, but was not significant for students in Achievement Level III (see table 6.2).
Of particular note was the quality and depth of responses provided by many of the students in the experimental section who, through their performance in the course, were identified by their instructor as low-achieving. Responses by Abby and Jim typify the explanations offered by students in the experimental section:

Fluorine is stronger than iodine (and) is able to take electrons away from iodine. (Abby, experimental section, Achievement Level I)

The fluorine has higher ionization, takes the electron from iodine. (Jim, experimental section, Achievement Level I)

While Abby and Jim’s explanations are incomplete, they do illustrate an effort to present the relevant concepts and properties of the atoms. Even more encouraging was the fact that a number of the lower-achieving students in the experimental section wrote thorough, well-positioned explanations that compared favorably with those of the higher-achieving students. Megan and John, who participated in the Pirate Ship analogy, gave clearly articulated responses to the halogen question that reflect a high degree of conceptual understanding:

Reaction (ii) would occur because fluorine would gain iodine’s electrons because it has a stronger attraction than iodine. Radius is smaller, pulling electrons closer to the nucleus. (Megan, experimental section, Achievement Level II)

Both have the same effective nuclear charge, however iodine has a larger number of protons/electrons as well as a larger atomic radius. Since fluorine has a smaller atomic radius and the same effective nuclear charge, it will attract and take valence electrons from iodine in a given reaction. (John, experimental section, Achievement Level II)

Most of the lower-achieving students from the comparison group, who were taught via a teacher-generated analogy, gave superficial answers to the question. Some students did not try to give science-based explanations, and relied on memorization of classroom procedures, as shown by Anne and Carly’s responses:
These two substances would react with each other because one of our labs was to mix these two chemicals together; the reaction was a colour change. (Anne, comparison section, Achievement Level I)

I pick (i) because I think I’ve seen that used before. (Carly, comparison section, Achievement Level I)

Other lower-achieving comparison group students gave explanations based on inappropriate and confused interpretations of science concepts:

They would not react because they share the same group, therefore share similar characteristics. Reactions occur when two different substances from different groups react . . . metals usually react with non-metals. In this case there are two non-metals with the same charges. (Carter, comparison section, Achievement Level II)

They are all metals and negatively charged, so they do not attract each other (Arlene, comparison section, Achievement Level II)

The quality of these students’ responses, and their low coded values for indicators of conceptual understanding referred to earlier, reflect the difficulties that lower-achieving students encounter in understanding and explaining difficult science concepts.

Table 6.2. Mean of Coded Values for Student Performance on the Halogen Test Question for Experimental and Comparison Groups.

<table>
<thead>
<tr>
<th>Achievement Level</th>
<th>Experimental Group Mean Value (max. 5.00)</th>
<th>Comparison Group (composite of all sections) Mean Value (max. 5.00)</th>
<th>t-test analysis p values</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.00 (n = 3)</td>
<td>0.10 (n = 10)</td>
<td>0.00057</td>
</tr>
<tr>
<td>II</td>
<td>2.33 (n = 3)</td>
<td>0.33 (n = 9)</td>
<td>0.0091</td>
</tr>
<tr>
<td>III</td>
<td>1.29 (n = 7)</td>
<td>0.74 (n = 19)</td>
<td>0.22</td>
</tr>
<tr>
<td>IV</td>
<td>2.83 (n = 6)</td>
<td>1.25 (n = 12)</td>
<td>0.022</td>
</tr>
<tr>
<td>I + II</td>
<td>1.67 (n = 6)</td>
<td>0.21 (n = 19)</td>
<td>0.00033</td>
</tr>
<tr>
<td>III + IV</td>
<td>2.00 (n = 13)</td>
<td>0.94 (n = 31)</td>
<td>0.0089</td>
</tr>
<tr>
<td>All Levels</td>
<td>1.89 (n = 19)</td>
<td>0.66 (n = 50)</td>
<td>0.000062</td>
</tr>
</tbody>
</table>
Student Performance on the Electron Affinity Test Question

Steven designed the electron affinity test question to assess whether students could apply their knowledge of halogens to problems set within a new context. Mean coded values of student responses for the electron affinity test questions are presented in Table 6.3 for both the experimental and comparison sections. I discuss the performances of lower-achieving and higher-achieving students separately.
Table 6.3. Mean Coded Values for Student Performance on the Electron Affinity Question for Experimental and Comparison Groups.

<table>
<thead>
<tr>
<th>Student Achievement Level</th>
<th>Experimental Group Electron Affinity Question Mean Value (max. 5.00)</th>
<th>Comparison Group Electron Affinity Question Mean Value (max. 5.00)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.00 (n = 3)</td>
<td>0.30 (n = 10)</td>
</tr>
<tr>
<td>II</td>
<td>1.00 (n = 3)</td>
<td>0.44 (n = 9)</td>
</tr>
<tr>
<td>III</td>
<td>0.86 (n = 7)</td>
<td>0.68 (n = 19)</td>
</tr>
<tr>
<td>IV</td>
<td>3.00 (n = 6)</td>
<td>1.50 (n = 12)</td>
</tr>
<tr>
<td>I + II</td>
<td>0.50 (n = 6)</td>
<td>0.37 (n = 19)</td>
</tr>
<tr>
<td>III + IV</td>
<td>1.85 (n = 13)</td>
<td>1.00 (n = 31)</td>
</tr>
<tr>
<td>All Levels</td>
<td>1.42 (n = 19)</td>
<td>0.72 (n = 50)</td>
</tr>
</tbody>
</table>

**Performance of Higher-Achieving Students**

The highest achieving students in the experimental group (Achievement Level IV) demonstrated a significantly higher level of conceptual understanding on the electron affinity question than their counterparts of similar achievement levels from the comparison group. Their mean coded value of 3.00 out of 5.00, was found to be significantly different than the 1.50 out of 5.00 recorded for the comparison group, using a two-tailed t-test analysis ($p = 0.010$). These results suggest that highest-achieving students in the experimental group were better able to transfer their understanding of interactions between the nucleus and electrons from the analogy-related example to the novel situation represented by the electron affinity question. However, experimental group students in Achievement Level III did not perform as well on the electron affinity question. The mean coded value for these students was 0.86 out of 5.00, and 0.68 out of 5.00 for the comparison group. A two-tailed t-test analysis indicated that this difference was not
statistically significant \((p = 0.65)\). Still, other differences relating to students’ understanding were apparent when student responses were compared.

Analysis of student responses in the comparison group indicates that forty-five percent of higher-achieving students (Achievement Levels III + IV) incorporated the octet rule in their explanations of the electron affinity question. The octet rule is a simplistic, non-explanatory rule, often found in introductory chemistry textbooks, that incorrectly implies that having a filled outer shell of electrons automatically “produces” stability for atoms and ions (Spier-Dance, Khan, & Dance, 2005). An answer given by Toby, a student from the comparison group, who was taught via a teacher-generated analogy, is representative of how students used the octet rule to explain the electron affinity trend:

As you go across the row, electron affinity increases. This is because the electron shells are getting full and the element wants to become more stable. Li has one electron and low electron affinity because it is easier to lose one electron to become stable. Fluorine needs one more electron to become stable, and therefore has a higher electron affinity. (Toby, comparison section, Achievement Level III)

Similar misapplication of the octet rule by students has been reported in other studies (see e.g. Coll & Treagust, 2002).

In contrast, no students in the experimental group made similar reference to the octet rule in their answers. Reasoned explanations by students in Steven’s experimental group made reference to the attraction exerted by the nucleus on outer-shell electrons. For example the following answer was given by Julia who participated in generating and dramatizing the Pirate Ship analogy:

As you go across the table from Li –F the ability to attract/gain electrons becomes greater because of the higher Zeff. Also the atoms get smaller and this helps them attract electrons better . . . (Julia, experimental section, Achievement Level III, June, 2004)
Performance of Lower-Achieving Students

The difference observed between higher-achieving students in the experimental and comparison sections wasn’t apparent for the lower achievers. Lower-achieving students in all sections (experimental and comparison) did not perform well on the electron affinity question. The mean coded value for lower-achieving students (Achievement Levels I + II) in the experimental section was 0.50 out of 5.00 on the electron affinity question. While this was marginally better than the combined mean of 0.37 for Achievement Levels I + II in the comparison group, a two-tailed $t$-test analysis of these values indicated the difference between the experimental and comparison sections was not statistically significant ($p = 0.67$).

The reference to the octet rule that was common among the higher-achieving students in the comparison group was not evident for the lower-achieving students who, generally speaking, failed to give any reasoned explanations. Overall, responses to the electron affinity question by lower-achieving students showed limited understanding of the concept and an inability to apply ideas they had studied relating to halogen oxidation. For example, Megan, a student from the experimental section, who participated in the Pirate Ship analogy, gave a conceptually strong response to the halogen question:

Reaction (ii) would occur because fluorine would gain iodine’s electrons because it has a stronger attraction than iodine. Radius is smaller, pulling electrons closer to the nucleus. (Megan, experimental group, Achievement Level II, June, 2004)

In contrast, Megan’s answer to the electron affinity question indicates conceptual confusion. She offered an accurate description of electron configuration and nuclear charge, but this was followed by an incorrect statement about atomic radius, which generally decreases across the periodic table. Megan also gave no explanation of electron affinity:

Li in the second row is $2s^1$ in electron configuration and Ne is $2p^6$ in electron configuration. As you move across the p. table the charge increases by one, but
Thus, it appeared that knowledge these students used when answering the halogen question was not drawn on when answering the electron affinity question.

**Nature of Analogy and Students’ Understanding**

To provide a more in-depth look at how the choice of analogy contributed to students’ conceptual understanding of halogens, I analyzed data from student interviews and analogy activity documents. I interviewed five students following the halogen analogy activity. Two had participated in the ‘Cruise Ship’ analogy, two in the ‘Beauty Pageant’ analogy and one in the ‘Pirate Ships’ analogy. For the limited number of students I interviewed, it appeared that the students’ level of understanding varied directly with whether the analogy they participated in corresponded closely to the target science concept.

The ‘Pirate Ships’ analogy showed close correspondence to the target, and was centered on the important theme that electron transfer between atoms is related to the differing force of attraction between the nucleus and electrons that exists for different atoms. During the analogy performance, two ships represented the elements iodine and fluorine, with individual pirates portraying individual atoms of the halogens. Balloons attached to the pirates’ clothing represented electrons, with eight balloons attached to the iodine pirate representing the filled outer electron shell of iodide, I\(^{-}\), and the seven balloons attached to the fluorine pirate representing the seven outer electrons of fluorine. This group’s analogy successfully mapped the relationship of sizes of the pirate ships to sizes of the halogen atoms and distance of the outer electron shell from the nucleus, and the gold over which the pirates fought represented the electrons for which the atoms were competing. Students whom I interviewed who enacted this
analogy were aware of, and able to articulate, the relationships between the analogy and the
target. The understanding of these relationships is apparent in Katie’s comments:

We have two pirate ships, each representing atoms. One ship is a large ship
representing iodine, because its outer shell is far away, and the small ship
representing fluorine because the outer shell is close. The two pirates will battle to
steal the electrons (gold) from iodine so fluorine can have all the gold. (Katy,
chemistry student, group discussion notes, written by the student, June 14, 2004)

The ‘Beauty Pageant’ analogy showed some correspondence to the target concept, with
the strength of attraction of different contestants for boyfriends representing the differing
attraction of atoms for electrons. For example, the ability of Flora Fluorine to more strongly
attract boyfriends than Ida Iodine clearly illustrated that a Fluorine atom will exert a greater
attraction for an electron than an Iodine atom. However, the analogy did not show other
important correspondences, such as the variation of atomic size, the number of outer electrons,
or the transfer of electrons between atoms. The students I interviewed who had been involved
with the Beauty Pageant analogy were able to offer reasoned explanations of their analogy, and
relate it to the science topic. This is illustrated by Michelle’s comments:

Our analogy is based on a beauty contest where the most attractive contestants
can attract boyfriends. Francis represents fluorine and she is the most attractive,
like Miss Universe and she steals the most boyfriends – which represent the
electrons. She needs the attention more so she tries harder. Claudia representing
chlorine is the runner up. Next is Brittany – like bromine and the third runner up
is Irene like iodine. Natalie – the sodium - repels suitors. (Michelle, chemistry
student interview, June 21, 2004)

Michelle was able to map the important relationships between the analogy and the target
concept. She understood that contestants represented different halogen atoms, and that the
competition for boyfriends represented a competition between atoms for electrons. Using the
symbols of the elements, F, Cl, Br, Na as the first letter of the names of the contestants, appeared
to be a learning aid, as Michelle actively drew upon this information when using the analogy as a tool to explain the science concept.

The third enactment (the Cruise Ship) lacked close congruence between the analogy and the target. Spaces in life rafts represented spaces in each atom’s outer electron shell, and the surviving passengers represented electrons that could be transferred between atoms. However, there was no relationship between the numbers of passengers in different life rafts and the numbers of electrons in different atoms, and the reason for passengers transferring between different life rafts was not related to the attractions exerted by halogen atoms on outer shell electrons.

The choice of the Cruise Ship analogy was dictated by one group member, Trevor, who based his analogy on recollections of an analogy that a teacher had used in a class some years earlier:

Yes, factually had to learn that a long, long, time ago and I thought that it was in high school that someone had used that analogy 18+ years ago, it wasn’t exactly the same, but it was to do with boats in the water. It was a teacher-generated analogy. (Trevor, chemistry student interview, June 23, 2004)

I observed that Trevor dominated other group members, and in his interview comments he mentioned that, based on his military background, he felt that it was important for someone to take charge of situations. Despite having based his analogy on a previous example (provided by a teacher), Trevor was, during his interview, unable to clarify the significance of many aspects of the analogy, or how they related to the science concept:

The numbers were supposed to represent the electrons; we had only so many people, so the numbers represented the numbers of people in the boats at the time. So there were 14 people in a 10 man boat, but what was happening was the boat was starting to take on water because it was too heavy, so there were 2 other boats that could carry 4 people each that only had 2 people in them. So that was supposed to be the orbitals that had a vacant position for an extra electron. (Trevor, chemistry student interview, June 23, 2004)
Trevor did not explain why he chose the numbers 14, 10 and 4 to represent the number of people in different boats, and the presence of too many people in a boat (14 in a 10 man boat) did not show close correspondence to aspects of halogen chemistry.

Still, Trevor believed that other students in the group had understood the analogy:

When I explained it to them they were - okay that all makes sense so they all understood the concept behind it, and they said lets go with that. That sounds great. (Trevor, chemistry student interview, June 23, 2004)

However, in-class comments from Trevor’s group members as well as interview comments from students in the audience showed that his peers were confused about the meaning of this analogy. This confusion is illustrated by the comments of Julia, a member of the audience:

I didn’t really figure out the (Cruise Ship analogy) . . . I was thinking okay what are they trying to say here? (Julia, chemistry student interview, June 23, 2004)

In summary, students who developed and performed the Pirate Ship and Beauty Pageant analogies, which showed close correspondences to the science target, were aware of relationships between the analogy and the target, and exhibited understanding when talking about their analogies. Students who participated in the Cruise Ship analogy, which did not show close correspondence to the target concept, were confused about the meaning of the analogy, and could not identify relationships between the analogy and science target.

To gain further insights into the relationship between students’ conceptual understanding of the halogen concept and the nature of the analogy they participated in, I analyzed each small group’s performance on the test questions. I compared coded values for students’ responses to the halogen exam question across the groups. I found that students who participated in the Pirate Ship analogy had higher coded values than students who participated in the Beauty Pageant, who had higher coded values than students who participated in the Cruise Ship analogy. The mean coded value on the halogen question for students from the Pirates Ships group was 2.67 out of a
maximum of 5.0, while the corresponding value for students who enacted the Beauty Pageant was 2.00, and 1.29 for those who participated in the Cruise Ship analogy. The difference in coded values for students in the Cruise Ship group, compared with those in the Pirates group, is statistically significant ($p = 0.029$). This difference was observed for both lower-achieving students and higher-achieving students. For example, the average coded value on the halogen question for higher-achieving students from the Cruise Ship group was 1.33 out of a maximum of 5.0, while the corresponding value for higher-achieving students involved in the Pirates analogy was 3.33. This difference in coded values is statistically significant ($p = 0.018$). The difference in mean coded values for students in the Cruise Ship and the Beauty Pageant groups is not statistically significant ($p = 0.37$).

These results for the three student groups suggest that conceptual understanding is impacted by whether the analogies show close correspondences to the target science concept. The Pirate Ship analogy showed close correspondences to the science target, and students in this group exhibited significantly higher conceptual understanding than students who developed the Cruise Ship analogy, which did not show close correspondences to the science target. The Beauty Pageant analogy was more clearly understood by students than the Cruise Ship analogy, but showed limited correspondences to the science target. Students in the Beauty Pageant group did not exhibit the depth of understanding shown by their counterparts who developed the more powerful Pirate Ship analogy.

**Overview of Student Understanding of the Halogen and Electron Affinity Topics**

My findings suggest that use of student-generated and performed analogies as a pedagogic strategy supported improved understanding of the halogen concept by all students. Lower-achieving students in the experimental group attained significantly higher coded values
than students in the comparison group on the exam question relating to the halogen topic. The reasoned conceptual explanations provided by lower-achieving students in the experimental group and the absence of such explanations by their counterparts in the comparison group is further evidence of the educational value of student-generated analogies.

The highest-achieving students (Achievement Level IV) in the experimental group performed better than their counterparts in the comparison group on the halogen exam question, and coding of answers for indicators of conceptual understanding showed that this difference was statistically significant. Experimental group students in Achievement Level III did not perform significantly better than their counterparts in the comparison group. These findings suggest that involvement in the analogy activity was most beneficial for lower-achieving students, and that the most able students also made significant gains in understanding. For middle-level performers, less difference was apparent.

Students' gains in conceptual understanding appeared to be related to whether the analogy they developed and enacted exhibited clarity, and showed close correspondence with the science target. Students who developed and performed analogies that showed close correspondences to the target concept were better able to articulate during interviews how their analogies related to the science concept than students whose analogy did not show close correspondences to the target. While this finding was based on the very small sample of students who volunteered to be interviewed, the difference in understanding that was observed was also reflected in students' performance on the halogen exam question. Students whose analogy did not closely correspond to the target concept received significantly lower coded values for their responses to the halogen exam question than students whose analogy exhibited close correspondence.
Analysis of the electron affinity question (Table 6.3) indicated that the highest-achieving students (Achievement Level IV) in the experimental section were better able to apply ideas they had studied relating to halogen oxidation to the electron affinity topic than their counterparts in the comparison sections. The inability of lower-achieving students in the experimental group to apply their understanding of halogens to the electron affinity question is disappointing, but reflective of the challenges of promoting deep understanding that can be transferred and applied to new problems (Senk & Thompson, 2002).

**Learning about the Immune Response through Analogies**

Four groups of students (n = 29) participated in the immune response analogy activity. Two groups of students chose to devise and perform analogies representing the humoral immune response and two groups chose to represent the cellular immune response. Students from the groups depicting the cellular response indicated that they had chosen this topic because it was the simpler one to depict. Students choosing the humoral response indicated their decision was based on their desire to use the activity to further their understanding of a topic they had found confusing and difficult. The analogies generated by each group of students are described in Table 6.4.

**Student Understanding of the Immune Response**

I coded students' responses to the pre- and post-intervention questions set by Anne, looking for sequencing of related events in the immune response. The coding criteria used were those discussed previously in chapter 4. Results of my analysis for individual student responses are shown in Table 6.5.

The data indicate that prior to the analogy activity very few students were able to describe a logical sequence of events for the immune response. Only 15% of the students (4 out of 27) were
able to describe four or more related immune response events (scored as 3 or 4) prior to completing the analogy activity, and 67% of the students (18 out of 27) failed to sequence any events. These findings suggest that the lecture and assigned reading from the text on the topic of immunity were of limited value in promoting conceptual understanding of the topic.

Students incorporated more sequences of related events in their post-intervention responses than in their pre-intervention responses. Post-intervention data indicate that 41% of students (11 out of 27) could describe a sequence of four or more related events. The number of students who included no sequencing of related events dropped to 33% (9 out of 27). These differences between pre- and post-intervention coded values are also reflected in the overall class averages, with students incorporating more sequences of related events in their post-intervention responses (1.9) than in their pre-intervention responses (0.78). A two tailed t-test analysis of the pre- and post-intervention sequencing values indicates that the observed difference in values was statistically significant ($p = 0.00049$). These findings suggest that participation in the analogy activity was accompanied by enhanced conceptual understanding.

Ten students volunteered to talk with me following the analogy activity. Two of these students had shown an improvement in coding values of at least three points. Seven of the students I interviewed had made no gains in coding values following the analogy exercise, and five were unable to sequence any events in their pre- and their post-analogy responses. Improved post-intervention values appeared to be related to two elements of the pedagogical intervention: 1) how closely the analogy corresponded to the target science concept, and 2) the nature of a student's involvement in the production of the analogy.

The 'Foreign Agent' analogy showed close correspondence with the target, and represented most of the important events in the immune response that appeared in the students' textbook. For example, the analogy included processing of antigen by an infected cell,
presentation of processed antigen on the cell surface, recognition of this antigen by a T cell, cloning of T cells and the role of B cells. The group narrator explained the correspondence of each part of the analogy performance to events in the immune response.

Students who generated and enacted this analogy exhibited a well-developed understanding of the science concept in their post-intervention responses. Of the five students involved in this analogy whose pre-intervention responses were assigned coded values of zero, three received post-intervention coded values of 3 or 4. Their understanding of both the science concept and the significance of the analogy was apparent during interviews. This is illustrated by Misha’s discussion of the analogy:

(Jean) had all the pink balloons on her, she was our antigen. Then (Ashley) came in she had the white balloons, she was the macrophage. So she was going to engulf the (antigen), so she had a safety pin and popped all of the balloons and took the streamers, because it said that they are processed and displayed and we didn’t have any way of displaying it so what she did is tear off the streamers and then she had them, like displayed antigen. So then our T cell came and recognized our displayed antigen and oh first (Ashley) had little bits of paper that were like the interleukin that she was throwing those around for the T cells, the T cells recognized it, then also had cytokines-more confetti-pink and blue, so then we had another guy that was supposed to show that the T cells were cloning because we had more than one. Then the B cell processes and displays antigen which is recognized by a T cell. Then again the T cells release cytokines-more confetti, causing the B cells to proliferate . . . Then at the end she had pink confetti that were the antibodies that were released by the plasma cell when she threw them around to show they were spread out. (Misha, biology student, interview, March 18, 2003)

Misha was able to provide a rich, detailed description of the analogy performance, and paid close attention to the correspondence between the analogy and the target. She was aware of the significance of events in the analogy performance, such as using confetti to represent the release of antibodies by plasma cells. During the analogy performance Misha acted as narrator and she commented that her role made her concentrate on the development of the analogy.
The “Jurassic Park” analogy was entertaining, but lacked detail and did not show a close correspondence between the analogy and the immune response target. The analogy did not represent important events in the immune response, such as the processing of antigen by an infected cell, presentation of processed antigen on the cell surface and recognition of this antigen by a T cell. The analogy was also confused, because it contained depictions of both the cellular response (antigen infecting cells) and the humoral response (a macrophage engulfing antigen).

Five of the seven students in the “Jurassic Park” group showed no improvement in coding values following the analogy exercise. The incomplete understanding exhibited by these students in their written responses was also apparent during interviews. The two “Jurassic Park” group members who were interviewed had incomplete understanding and were confused about the significance of elements of their analogy. This is illustrated by Mary’s comments:

This is a macrophage so she engulfs (the antigen) and then I don’t really understand what the process is but she engulfs it and then tells the T cells how to kill them, and then the T cell was able to abolish them... It doesn’t make sense to me... The gist that I got out of the (performance) was that when an antigen was recognized, T cells proliferate, B cells proliferate and they destroy, that’s what I understood. (Mary, biology student, interview, March 20, 2003)

Mary was unable to identify important events in the immune response, such as presentation of processed antigen bound to proteins on the cell surface and how infected cells are destroyed by T cells. These events were not clearly represented by the analogy.

During the analogy activity, Mary acted as the group recorder, and was the narrator during the performance. She believed that this involvement improved her understanding:

Because I was the writer and I had to understand what was going on in my play, so I had to make sure that everyone was doing their thing, so that kind of made it go together. (Mary, biology student, interview, March 20, 2003)
<table>
<thead>
<tr>
<th>Science Topic</th>
<th>Analogy Theme</th>
<th>Analogy Description and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellular</td>
<td>Cops and Robbers</td>
<td>Robbers (invading antigens), wearing white arm badges, take their place around the table at the front of the room. They ask each other “How many guys did you infect yesterday?” They reply, “We’ve been pretty busy”. The sheriff (a T cell) approaches, wearing a large star shaped badge, and asks, “Are you going to be hanging around for a while longer?” “Well what are you going to do about it?” the robbers ask. “Well if you guys are hanging around I will go and get some backup,” replies the sheriff. The sheriff calls for backup (“T” cells). When backup arrives with green arm badges they aim their hands like guns at the ‘bad guys’ and pop balloons at the same time.</td>
</tr>
<tr>
<td>Humoral</td>
<td>Mr T Cell</td>
<td>An evil villain Auntie Jen (invading antigen) encounters Mac-Phagy (a macrophage). Mac-Phagy wraps Auntie Jen up with tape (phagocytosis). Then, Mr. T Cell walks by and recognizes a colored scarf worn by Mac-Phagy (processed antigen bound to MHC protein). This causes Mr T Cell to call in the T Squad, by giving T Cell labels to two students (proliferation). The T squad then causes serious damage to Auntie Jen by using immobilizing tape and towel whipping (endocytosis). We are told that Immunity City is saved.</td>
</tr>
<tr>
<td>Humoral</td>
<td>A Foreign Agent</td>
<td>A foreign agent (foreign cell) with pink and white balloons attached (invading antigen) enters and is approached by another student with white balloons (the macrophage), who says, “I am going to engulf you” and pops some of the foreign agents pink balloons. The narrator says that the antigen has been taken up by phagocytosis and degraded. Another student (labeled T cell ) recognizes the pink balloons (processed antigen and MHC protein on the macrophage) and pops some balloons. Another person enters (a helper T cell) and introduces more people labeled as T cells (clones). The narrator tells the audience that the binding of the antigen triggers endocytosis, degradation and further display of the processed antigen. The T cell throws blue pieces of paper (cytokines) over two more people labeled as B cells, which we are told then proliferate, differentiate and eventually form antibodies.</td>
</tr>
</tbody>
</table>


Table 6.5. Student Responses to Immune System Questions.

<table>
<thead>
<tr>
<th>Student (n=27)</th>
<th>Pre-intervention Sequencing /4</th>
<th>Post-intervention Sequencing /4</th>
<th>Net Change</th>
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</tr>
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<tr>
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<td>3</td>
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<td>Jean</td>
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</tr>
<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hailey</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>John</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Liz</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mary</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Seth</td>
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<td>0</td>
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</tr>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>Ashley</td>
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</tr>
<tr>
<td>*Column Average</td>
<td>0.78</td>
<td>1.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Of the 29 students who participated in the analogy performance, 27 completed both the pre and post-intervention questions.
However, while Mary understood “the play”, her self-appointed role as recorder did not require deep understanding of the topic:

Thank goodness, one of the people in our group-he’s a genius and he knows everything so he knew what was going on anyway, so from that when I wrote it down I was like oh this is what happens. (Mary, biology student, interview, March 20, 2003)

Thus, Mary relied on the group leader to develop the analogy, and did not engage sufficiently with the content to develop her own understanding of the topic. So, even after reading and participating in the analogy activity, Mary remained confused about many aspects of the immune response.

The humoral response and the cellular response are still fuzzy and reading the chapter helps nothing... All these words, all these hormones, these can be picked up later nobody cares about the hormones. I don’t even understand it. (Mary, biology student, interview, March 20, 2003)

Mary’s failure to learn about the immune response, even though she appeared to be participating fully, illustrates how involvement in these student-centered activities must be carefully monitored.

Interview data indicated that students who performed well on post-intervention probe questions had been actively involved in the construction and performance of their analogy. For example, Donna’s pre-intervention response was assigned a coded value of zero, and she received a post-intervention coded value of 3. She was not only active in her group’s discussions, but also acted as group leader:

We discussed doing (my idea for an analogy) and a guy’s in my group - people picked the two, then we discussed things about who was going to be what, then I told people who was going to be what. (Donna, biology student, interview, March 21, 2003)

Donna also assumed the major role of a sheriff during the performance. In describing the performance, she was able to recall many events in detail:
We have the infected cell, and the MHC proteins that are recognized by the T cells- which would have been us... *(Cells)* get infected, then they get recognized and then the T cells proliferate and that's when the sheriff gets all his deputies and then *(infected cells)* get lysed. Some wrist bands represented the MHC proteins. I proliferated so now these are all the T cells then we all checked the wrist bands - one girl with a green wrist band was recognized as not being infected. *(Donna, biology student, interview, March 21, 2003)*

Donna was also aware of finer correspondences between the analogy and the target concept, such as the use of wristbands to represent MHC proteins, and of their significance in immune response events.

Students’ interest and involvement in the analogy exercise did not, however, automatically lead to gains in conceptual understanding. This was shown previously through Mary’s experience. Although eight of the ten students interviewed indicated that they found the activity to be an enjoyable way of learning, and seven students specifically commented that participation in the analogy had made the science “memorable” by giving them a mental picture they could refer to, five students received coded values of zero on the post intervention response. One of these students, Seth, was actively involved in his group’s performance of the ‘Jurassic Park’ analogy, taking the major role of a velociraptor. He viewed this active involvement as important in promoting recall, and later talked at length about the events:

These are T cells and these are tissue cells, and I come in, but I don’t actually kill the tissue cells I just infect the tissue cells. I’m just an invading virus *(a raptor virus)*. The T cell notices me and I am familiar to the T cell, so the T cell has no problem killing me. But for the next two people that walk in, they’re a new virus that the T cell is not familiar with, so we use the jacket as a symbol that the jacket is protecting him, they don’t know where to hit him, as he has the jacket on. So the T cell runs. Then the macrophage comes and engulfs them, and then hands over to the next T cell the identity of these ones, so then the macrophage has a way of getting rid of them, so instead of shooting them in the jacket the T cells have learnt to shoot them in the face. *(Seth, biology student, interview, March 20, 2003)*
However, Seth’s participation in the Jurassic Park analogy did not lead to improved understanding. During his interview, he was able to recall aspects of the performance, but could not give information on how the various immune response events took place. In addition, he could not separate the attributes of the analogical model (the actors) from that of the target. Thus, Seth’s recall seemed to be related to the analogy performance, but not to the target science concept.

**Overview of Student Understanding of the Immune Response Topic**

Analysis of pre- and post-intervention responses and interviews suggests that for some students, conceptual understanding of the immune response was aided by their involvement in the analogy exercise. Individual students made large gains in conceptual understanding. For these students, this learner-centered, participatory small group activity may have provided a classroom situation that encouraged learning. Gains in conceptual understanding were also influenced by the choice of analogy. Analogies that clearly depicted major events in the immune response, and showed correspondence between the analogy and the target, were associated with improved understanding of the immune response, and students who demonstrated this improved understanding were able to explain the analogy they had developed and performed, and show how it corresponded to the science target.

A majority of students viewed participation in the analogy performance as an important aid to learning. However, active participation in the analogy activity did not necessarily lead to improved understanding. Students that developed and performed an analogy that lacked correspondence with the immune response target exhibited incomplete understanding of the immune response in their post-intervention responses.
Overall Summary

Students in both Anne's and Steven's classes made gains in conceptual understanding following their involvement in the analogy exercises. While most students exhibited improved understanding after the analogy exercise, changes in understanding were most pronounced for certain groups. I found that high-achieving chemistry students were able to apply their new understanding both to the halogen question, which related directly to the analogy science topic, and to the less closely related electron affinity question. This ability to transfer knowledge is an indicator of strong conceptual understanding. While lower-achieving chemistry students showed gains in understanding of the analogy-related topic, they were unable to transfer this knowledge to new learning situations.

Improved understanding occurred when students' analogies clearly represented important features of the target, and showed close correspondences to the target concept. Students who were actively involved in the development and performance of such analogies understood how their analogies related to the science topic better than students whose analogies did not show close correspondences to the target concept. Students' understanding of the science topic was limited when their analogies failed to convey important relationships to the target.

Students' interest and participation in the analogy exercise did not always lead to gains in conceptual understanding. Students who were actively involved in the analogy performance, but did not engage intellectually with the science target during analogy development, did not develop their own understanding of the topic.

Thus, a number of elements appeared to work together to influence conceptual understanding. Some, such as the way participation is constructed and monitored, relate directly to pedagogical and procedural aspects of the analogy intervention. These can be directly managed by the classroom instructor. Others, such as the ability of students to engage
intellectually with the science topic, are not directly related to design or implementation of the analogy exercise.

Having demonstrated that this student-centered performance-based activity can promote understanding of complex science topics, I next consider students’ and instructors’ perspectives on using this type of analogy activity within the post-secondary classroom. Participants’ views of learning and learning experiences influence how and whether learning occurs; they also can provide information on how and why the analogy activity enabled learning.
CHAPTER SEVEN
STUDENTS’ AND INSTRUCTORS’ PERSPECTIVES ON USING STUDENT-GENERATED AND PERFORMED ANALOGIES

In chapter 6, I addressed my first research question relating to the ways that student-generated and performed analogies can help college students to understand complex and abstract concepts in their science courses. In this chapter, I present my analysis of data relating to the perspectives of both students and instructors on the use of these student-generated analogies. I specifically address my second research question:

*What are the perspectives of college students and instructors on learning science using performed analogies?*

In answering this question, I draw upon data from interviews with individual students and instructors, and from in-class observations, as well as videotapes of the performed analogies. I investigated how students’ view their involvement in the analogy exercise, and how their views on learning influence their participation in the activity (Spier-Dance & Mayer-Smith, 2004). From my analysis, I identify elements of the analogy activity that influence student interest, and I discuss students’ views about learning using analogy activities.

After examining students’ perspectives, I consider the views of the instructors. While the instructor is a dominant influence in the classroom, instructor’s beliefs and actions are affected by what occurs in the classroom. I describe instructors’ perceptions of using performed analogies to promote student learning and identify the issues they perceived as impacting the introduction of this strategy in the post-secondary science classroom.

Based on my analyses, I consider how students’ and instructors’ views inform introducing this strategy into the post-secondary science classroom, and conclude with suggestions for
researchers and instructors interested in the implementation of small group, interactive activities, such as student-generated and performed analogies, in post-secondary science settings.

**Students' Experiences and Perspectives on the Analogy Activity**

Students' views on the analogy activity were generally positive. Analysis of interview data revealed that most (96%) valued the analogy activity. A majority of students interviewed (71%) indicated that their experience with analogies was enjoyable and 96% believed that it promoted understanding. Their views emanate from their experiences in both the small-group work and performance aspects of the activity they were engaged in. In what follows, I discuss students' perspectives on small-group analogy development activities and the performances, using quotes from interviews and written work to represent the participants' voices. I then consider how these views inform bringing this pedagogical approach into the undergraduate science classroom.

**Students' Perspectives about Small-Group Work**

The opportunity to work in small groups was viewed positively by students. Thirty-three percent of students interviewed commented that social interaction during the small group discussions was an important benefit provided by the analogy activity. Their drawing attention to such interactions suggests similar opportunities are lacking in the traditional post-secondary science classroom, which is dominated by an instructional paradigm that isolates students from each other. Sylvia's comment illustrates how interactive activities can help to counter this isolation:

*(During the analogy activity) you have an interaction between other people - the barrier between the students is broken too, it helps to get to know each other.*

*(Sylvia, chemistry student, interview, June 19, 2003)*
Students discussed how time spent in developing the analogies, and in the subsequent sharing of ideas during their performance, contributed to an increased feeling of community. Some students, like Linda, expressed strong sentiments about the personal value of getting to know their peers:

... that is one of the things I love most about group work ... I come away from it knowing those students far better than I ever would otherwise and that to me is very beneficial on its own. (Linda, biology student, interview, June 19, 2003)

This community-building offers important benefits. Students who feel part of learning communities exhibit enhanced self-confidence in their studies, and learn to appreciate other students’ perspectives (Gabelnick, MacGregor, Matthews & Smith, 1990). Tinto, Love and Russo (1994) found that students in three college programs that emphasized the building of learning communities exhibited significantly lower drop-out rates than control groups in more traditional programs. Students in the learning community programs also achieved higher grade-point averages than those in the control groups, suggesting that students who are part of a community of learners have an increased chance of success in college courses. Taken together, this research points to the importance of designing and implementing strategies that foster community in post-secondary science settings.

**Students’ Views on Performance**

Students are rarely involved in performance-based activities within the undergraduate science classroom, where attention is often centered on the instructor. I was therefore interested in how students viewed their involvement in the analogy performance. Valuing of interactive and social aspects of the analogy activity was apparent in students’ views relating to the analogy performances. Fifty-eight percent of students interviewed indicated that they enjoyed and saw educative value in performing the analogies. The impact of participating is illustrated by Paul’s comment:
(Our performance) is going to stay in my mind for a very long time because I am going to relate it to how funny it was to watch other people do that and to do it ourselves. (Paul, biology student, interview, March 21, 2003)

Students who enjoyed performing also perceived that their participation promoted understanding. For some, this came from physical involvement, or what other researchers have termed embodied experience (Fels & Meyer, 1997; Varela, Thompson & Rosch, 1993):

I think when your whole body is involved in learning. You are going to remember it more because it is an experience and not just “here, feed me”. (Una, biology student, interview, June 17, 2003)

My long-term memory of it will be stronger because of the acting of it, because you remember more things that you have done physically, than memorizing from a piece of paper... (After the activity), I went back to that acting scenario and it makes things easier – when you hear them, then you can visualize them and then you remember them. (Donna, biology student, interview, March 21, 2003)

For others, their active, embodied involvement provided new perspectives that helped to clarify the science concept. Students recognized, and could articulate, how the activity of enacting an analogy made the concepts more accessible:

Performing it gave me a new perspective. When you do it, the concept becomes a lot clearer. For example, the molecules banging on the walls or on the container is clearer. (Sylvia, chemistry student, interview, June 24, 2003)

When preparing for their analogy performances, students were aware of the presence of the audience. For example, they felt the need to entertain their audience and considered that if the performances were entertaining this would promote engagement and make the material more memorable:

... these (analogy performances), they keep your attention because everyone’s trying to be funny and make it humorous, because then that’s what you’ll remember, so you’ll be like “oh yea that was funny when this happened”... (Mary, biology student, interview, March 20, 2003)
Many students (54%) indicated they felt some tension associated with a concern that, when performing for an audience of their peers, giving a poor presentation would reflect badly on them, and cause them embarrassment:

... you are forcing students to be more involved. If they have to get up there in front of the class they don't want to look like a fool, by teaching something that is wrong, so they have to learn it. (Una, biology student, interview, June 17, 2003)

This tension prompted and stimulated most students' involvement in the learning process, because they felt obligated to understand the material in order to produce an acceptable analogy.

A smaller number of students interviewed (17%) indicated that they did not enjoy the performing aspect of the analogy activity. These students often found other ways to be involved in the activity, by acting as directors or narrators:

I'm not a huge person for getting up in front of the class and speaking, so I didn't care that I was the director. I volunteered to write it down - to make sure everyone had their spots. As long as I don't have to go up in public, I'm okay. (Mary, biology student, interview, March 20, 2003)

As described in chapter 6, some students combined these roles as narrator or director with active involvement in developing the analogy, but Mary relied on the group leader to develop the analogy. Her passive roles of recorder and narrator did not require deep understanding of the science concept, and she did not engage with the ideas that were being discussed.

**Motivation for Learning**

The social and novel performative aspects of the analogy exercise operated in tandem to promote interest and enjoyment for students; 71% of the students associated their enjoyment of the analogy activity with the opportunity to be involved in an innovative and stimulating...
classroom activity. In part, this motivation was related to relieving some of the boredom students associated with lecture-centered classrooms:

Well, we’re sitting around for 8 hours, just taking notes and listening to the teacher go on and on, there is some kind of release that we need. We usually find that outside of school, but if we can find it inside of school, it’s very helpful. (Paul, biology student, interview, March 21, 2003)

While no students denied the usefulness of lecturing, many expressed concerns that lecturing as the sole method of instruction failed to promote or maintain their interest in learning. Most students saw benefits in combining lecturing with other teaching techniques in order to give variety to the learning experience:

After half an hour I start to zone out when you are just being talked to, but when you can actually integrate yourself into an activity . . . then it’s easier to remember stuff that’s going on. (Donna, biology student interview, March 21, 2003)

Students saw small group activities as a way of providing this variety:

(During small group activities) . . . it’s not just sitting in the same place taking notes. You’re moving around you’re speaking with different people . . . it’s kind of motivation. . . . (Mary, biology student, interview, March 20, 2003)

Students’ motivation to learn was also provoked by the accessibility of analogies that they and their classmates had produced. Many students indicated that they could relate to student-generated analogies more easily than those chosen by instructors:

I think student-generated analogies are best. It’s not often that I will catch on to what a teacher is using as an analogy, just based on age and experience, they are quite a bit different to what I have experienced. (Pat, chemistry student, interview, June 17, 2003)

This view is consistent with the findings of Harrison and Treagust (2000), that student-generated analogies are more familiar and accessible than teacher-generated analogies.

Thus, this student-centered, interactive small-group activity provided an environment that students found not only enjoyable and interesting, but also motivational. Their comments also
hint at learning-related benefits, and I now consider the specific pedagogic benefits that students identified as related to their involvement in the analogy activity.

**Pedagogical Aspects**

**Alignment with Students’ Approaches to Learning**

Students’ views about the usefulness of the analogy exercise appeared to be closely aligned with their preferred approaches to learning. For example, many students (67%) identified themselves as ‘visual learners’, for whom a video, a demonstration or a physical model helps to improve recall, and helps to contextualize their learning. These students regarded the visual nature of the analogy activity, and their active, embodied involvement, as important in helping them to learn, and in clarifying what they did or did not know:

If I see (an analogy) in action (because) I am a visual person – the science concept together with the analogy makes more sense. (During the analogy performance) we moved around as molecules in the container, bumping the walls, and then when it was open into another container, that is where we made a mistake that we didn’t realize until later. (The performance) definitely made me understand it better. (Sylvia, chemistry student, interview, June 17, 2003)

Other students saw learning as being more holistic, requiring multiple inputs. For holistic learners, the student-generated analogy activity provided opportunities to bring together a number of different approaches to learning science. For example, Donna viewed herself as an eclectic learner:

I’m one of those people, I can learn best if I can do everything I possibly can, if I can discuss it with people, if I can read about it and if I can visualize it. Especially visualization, I will have no problem remembering stuff if I can visualize it. My long term memory of (the science concept) will be stronger because of the acting of the analogy, because you remember more things that you have done physically, than memorizing from a piece of paper. (Donna, biology student, interview, March 21, 2003)
Thus, for many students their active embodied involvement in the analogy activity, particularly its visual nature, provided situations and opportunities to learn that were closely aligned with their preferred learning approaches.

**Students Teaching Students**

A recurring theme in students’ comments was that they recognized the value of learning with, and from, other students during small-group activities. Many students (79%) identified small-group discussions as important in aiding their learning. For these students, the interchange of ideas that can occur within the social setting of small-group discussions was important in promoting understanding:

Yes, I value the interaction with other people; I think the interchange of ideas is awesome. I have learned so much from other people. (Linda, biology student, interview, June 19, 2003)

Student exchanges were dynamic and varied. Students asking and answering each others’ questions helped to clarify their understanding of the science:

I think the student-student interaction helped, because if one of us said something, someone would answer, and someone else would clarify and somebody may have just been listening. (Una, biology student, interview, June 17, 2003)

Students used small group discussions to test ideas with other group members:

It’s bouncing ideas off each other. I think that helps, because you don’t get that when you are just sitting there. (Una, biology student, interview, June 17, 2003)

Some students became active listeners during their small-group analogy activity, and recognized that this approach allowed them to gain insight from other group members:

As a tool, it (group work) is a good thing, as you get to see different people’s views. (Trevor, chemistry student, interview, June 23, 2004)
Other students adopted a leadership role, assisting their group members in understanding the science concepts involved in the analogy development. These teacherly students recognized the positive links between their own learning and peer-teaching, and believed that their conceptual understanding was enhanced when they taught the concepts to other students. Vicky, appreciated the opportunities that arose in small-group activities to explain concepts to other students. She saw instructing others as a way of enhancing her own learning:

"Discussing it . . . helps you think through the ideas, like when you are trying to learn something by teaching it to someone else, that helps you probably more than the person you are teaching because it helps you to think through the ideas and to learn it even more." (Vicky, biology student, interview, February 12, 2004)

For Carl, a high achiever, peer teaching was a valuable structure for self-assessment of understanding:

"If I look at material and just study it does very little for me, but if I take that material, study it and if I rewrite a lesson plan or website that is supposed to explain what I know, and then try to teach other people about it, or explain it to my sister, who is not in university, anything like that, fellow students who ask questions, it tests you. If you have just learnt a piece of material and you teach it to someone else who doesn't know it . . . it forces you to really know your material." (Carl, biology student, interview, March 26, 2003)

In many cases, interactions among students during small-group discussions mirrored the formal teacher/student relationship, with the student mentor taking on the teacher’s roles of coordinator, organizer, decision maker and disseminator of knowledge. “Mentor students” saw a need to bring other group members up to speed, so that they could more fully participate in the analogy activity. Other group members were willing to allow their self-appointed peer tutors to adopt this teacherly role, and typically viewed the resulting situation favorably:

"We had one guy in the group who is really smart, and had read the chapter before every class and he knew exactly what was going on, and he guided us and directed the play, and ended up helping out. I basically learnt everything on
Situations where students learn from students have been shown to be beneficial for both the “student-teacher” and the “student-learner”. Khan (in press), in a study of small-group learning in undergraduate chemistry classes, shows how peer mentors can provide a positive learning environment for other group members, and McKeachie (1998) argues that “... the best method of teaching ... is students teaching other students” (p. 43). Lundberg (2003), in a study of college students in various arts and science majors, found that time spent in peer teaching and small-group discussions was a strong predictor of their conceptual understanding.

There was also evidence that members of some groups underwent more complex role changes, when the rigidly defined and separate roles of student and teacher coalesced into a new entity of learner/teacher. Students were at different times both teachers and learners. This is illustrated by Paul’s comment:

It worked kind of well because half the time I was filling in the gaps, listening to the others, and then sometimes I was the guy who got to explain things. (Paul, biology student, interview, March 21, 2003)

Interview responses indicated that the students in this study were aware of the benefits that came from this melding of learning and teaching within a group. They spoke about how they learned through and by their conversations with their peers:

Everyone knew something that nobody else did know, so when we put that all together it worked out. (Mary, biology student, interview, March 20, 2003)

But not all students viewed student-student learning as beneficial. Consistent with the findings of other researchers who have examined peer teaching (see e.g. Buxeda & Moore, 2000; Tessier, 2004) a group of students (17 %) clearly preferred the traditional arrangement where the course instructor was responsible for providing knowledge:
I like lectures, as long as I can understand what the teacher is talking about . . . I like lectures, good notes to study off. (Seth, biology student, interview, March 20, 2003)

During the analogy activity, students like Seth adopted a passive learning approach, and allowed other students to adopt the teacherly role. They preferred to assume more modest roles, and often deferred to the views and opinions of other students they considered more knowledgeable. Still, these passive learners claimed that they enjoyed the small-group activity, and saw it as a motivational learning experience.

Patterns of Communication

When students participated in group discussions about analogies, patterns of communication between group members changed, with students becoming more willing to listen to, discuss, and question each other's knowledge. Some students became more actively involved in 'talking to learn' (Pedretti, et. al, 1998) and no longer accepted the automatic validity of statements and beliefs. There was evidence that students were more open to negotiating the validity of ideas:

Sometimes if one person said something that wasn’t quite right then someone would say this is a better way to say it, so there was input from everybody. It was helpful because then you had to think about what was more accurate and what was the best way to portray it. (Julia, chemistry student, interview, June 15, 2004)

Classroom interactions following participation in the analogy activity were noticeably different from previous dialogic dynamics, characterized by traditional patterns of passive acceptance of the teacher’s role as the primary authority and unquestioned judge of validity and correctness. The changes I observed in students’ communication patterns and roles in the classroom may be related to dialogic experiences that accompanied the analogy exercise. Before participating in generating and enacting their own analogies, the students typically assumed passive listening
roles, while the instructor lectured and controlled the pace and content of learning exchanges. Most students did not actively participate in lessons, and few contributed ideas or answered the instructor’s questions. In contrast, the analogy activity fostered students’ participation in small-group discussions. There was evidence of a more dynamic, effervescent classroom environment in which students were moving, talking, and laughing as they engaged in conversation about science concepts. While I did not collect data on whether the changes I observed were lasting ones, Anne volunteered that, in lessons following the immune analogy exercise, students continued to be more vocal during class and appeared to be more willing to discuss and question ideas. This suggests that the analogy activity may have contributed to new patterns of communication with students participating as more active learners in the science classroom. A similar relationship between involvement in performative, embodied activities and active learning has been observed by Harwood, MaKinster, Cruz and Gabel (2002), who found that college students’ involvement in role-playing during a simulated debate encouraged active learning, by prompting students to engage in enquiry and argumentation.

**Summary of Students’ Perspectives**

Students valued and enjoyed their participation in the analogy activity. Social interaction during the small-group activity was important, and time spent in developing the analogies, and in sharing ideas, contributed to an increased feeling of community. Encouraging community within the science classroom is important, because students who are part of a community of learners have an increased chance of success in college courses (Tinto, Love & Russo, 1994).

Students appreciated the opportunity to participate in an innovative, performance-based classroom activity. Students perceived that the participatory experience promoted understanding
of the target science concepts. Some attributed enhanced understanding to their physical embodied involvement, while for others, the visual nature of the analogy activity was important in aiding their learning of the science concepts. It appeared that the social and performative nature of the analogy activity motivated students to learn, by relieving some of the boredom associated with lecture-centered classrooms. Physical and visual elements of the analogy activity were closely aligned with some students' preferred learning approaches. The accessibility and comprehensibility of student-devised analogies, compared with those generated by instructors, provoked students' interest in learning and fostered understanding.

The majority of students identified the exchange of ideas within small-group discussions as contributing significantly to their understanding. In group discussions about analogies, new patterns of communication emerged. Many students became deeply involved in 'talking to learn'; and were more willing to listen to, discuss, and question each others' knowledge. Some adopted a teacherly role, and helped group members to understand the science concepts associated with their analogies. During group work, the rigidly defined and separate roles of student and teacher coalesced into a new entity of learner/teacher, in which students were, at different times, both teachers and learners. There was evidence that new roles and patterns of communication for students had some carryover into science lessons taking place after the analogy exercises were completed.

Instructors' Experiences and Perspectives on the Analogy Activity

Anne, Sue and Steven, the instructors who participated in this study, viewed their experiences with the analogy activity as worthwhile. They noticed and commented that student interactions and classroom dynamics changed during the analogy activities. Analogy performances provided opportunities for the instructors to gain insights into their students' understanding of the
science concepts. These opportunities were valued by the instructors. In the next section I discuss instructors’ perspectives on the use of analogies in their classrooms, in particular their views about the social aspects of the learning environment and their identification of alternate conceptions. I then consider how instructors’ views can inform efforts to introduce this pedagogical approach into the undergraduate science classroom.

**Attending to the Social Nature of Learning**

Anne, Sue and Steven recognized changes in the social dynamic of their classrooms during the analogy development work. They realized that students appreciated and enjoyed the opportunity to work together in a more informal and social learning environment. For example, Steven commented:

They (*students*) were much more social than I usually see (*in class*). Even in the lab they don’t get to do this group thing, which they obviously enjoyed. (Steven, chemistry instructor, interview, June 19, 2003)

Instructors viewed the increase in collegiality positively, and recognized that the analogy activity created opportunities for student interactions that were not present in traditional undergraduate science classrooms. The instructors also commented on the relaxed atmosphere that accompanied the analogy exercise. Anne was particularly pleased with the increase in collegiality among students fostered by the analogy activity. She had observed that community building was difficult in the post-secondary environment, but if collegiality was stimulated among students in first year classes there was a greater likelihood of cohort groups working cooperatively in subsequent classes throughout their biology degree program:

I think it was good making them work in these (*small*) groups, also trying to get them to work in a more informal setting. One of the things I am trying to create in my classes is this sense of collegiality . . . This would add to that collegiality, they can build on it for second year. (Anne, biology instructor, interview, March 12, 2003)
Sue observed that the analogy exercise encouraged students to be more vocal than in the traditional biology classroom. She noticed that after participating in the analogy exercise, students were communicating in different ways about science with each other, and were more willing to talk in class about their understanding:

It made (students) feed back to me more because we had done something so participatory. It made me think . . . that if you could do something that made them interact with each other more it may help their learning, because it makes them talk to each other. A social thing makes a really big difference. (Sue, biology instructor, interview, December 12, 2004)

Instructors' observations about community corresponded with the students' perceptions discussed earlier in this chapter, both groups indicating that the use of performed analogies promoted a stronger sense of community amongst students. The instructors' recognition of the value of social interactions and community-building is encouraging, particularly as there is evidence that college students who are part of a community of learners have an increased chance of success in their courses (Tinto, Love & Russo, 1994), and are less likely to drop out (Tinto, 1987).

**Attending to Alternate Conceptions**

All instructors noticed that some unexpected explanations and ideas about science concepts were revealed during the analogy exercises. They found that hearing and seeing these “alternate science conceptions” provided insights into students' thinking, and aided them in planning for instruction. For example, Steven detected a number of alternate conceptions as he watched his chemistry students perform their analogies on kinetic molecular theory and gases. One such conception related to the velocity of gas molecules when they escape from a small container into a larger container. During the analogy performance, students representing
individual gas molecules moved around more quickly, suggesting that molecular velocity increased, when in fact the velocity of a molecule would be unchanged. In his interview, Steven noted:

I was really surprised when the one group got into molecular velocities, and thought that the molecules would speed up when they escaped into a larger container. This was really obvious, when they were behaving like the molecules themselves. (Steven, chemistry instructor, interview, June 19, 2003)

Steven revealed this alternate conception to the class during a post-performance discussion, and decided to address it directly by explaining the scientifically accepted concept:

I would never have expected them to think like that, but when we talked about it afterwards, it seemed that most of them were pretty fuzzy on what would happen. It worked really well that we could discuss what was going on, and managed to straighten things out, so I think most of them were on the right track in the end. (Steven, chemistry instructor, interview, June 19, 2003)

By providing an opportunity to gain insights into the conceptions held by students in ways that are not attainable in a teacher-centered classroom, the analogy performances allowed Steven to reveal and discuss alternate conceptions. Such discussion can be a valuable aid to student learning (Nussbaum, 1985).

The other instructors did not deal with students’ alternate conceptions as directly as Steven. In some cases, when alternate conceptions were revealed, the instructor chose not to discuss them with the class, and a valuable opportunity to enhance students’ conceptual understanding was lost. In one instance in Anne’s class, time restrictions severely limited post-performance discussion and, thus, she was unable to discuss alternate conceptions with her students. A different situation came into play in Sue’s class. She noted that during one analogy performance representing meiosis, students were confused about the number of chromosomes produced in ‘daughter’ cell nuclei. However, Sue chose not to reveal the existence of the alternate conception to the students following the performance. During her interview, she
indicated to me that she was uncomfortable pointing out errors in students’ interpretations in front of the whole class. Sue’s reticence seems somewhat problematic if we accept research claims that conceptual change is fostered if prior alternate conceptions lose status, while scientifically acceptable conceptions gain status (Hewson & Hewson, 1992). Actually, Sue’s concerns may have been unfounded, because students indicated during interviews that they valued instructor input during post-analogy discussion, viewing this as a constructive aid to their understanding. Steven’s students commented on this point during interviews:

We did do one thing wrong. I said that when there is less pressure the molecules speed up and that was incorrect – they go at the same speed, just less collisions and what not – we had that wrong. I learnt the one point that (Steven) corrected us on. I wouldn’t have learnt it by myself. Basically, it just cemented my understanding. (Pat, chemistry student, interview, June 22, 2004)

Thus, it appeared that post-analogy discussions of student conceptions helped students to re-evaluate their understanding, with some conceptions gaining status, and other conceptions losing status. This identifies an important role that the instructor can play in promoting conceptual understanding.

Instructors’ Perspectives on Teaching using Student Analogies

Sue, Anne and Steven reflected on the pedagogy of the analogy exercise, and whether the exercise conformed with their thinking about teaching. All three instructors viewed the analogy exercise as a good fit with their preferred teaching approaches. Because my in-class observations and interviews indicate that there were significant differences in the teaching approaches used by the three instructors, I consider their views individually.

Anne encouraged collaborative learning in her classes, with small-group activities playing a central role in facilitating problem-based learning. During her classes, Anne routinely
alternated between short lecture-explanation sessions and small-group exercises. When covering mandated curricula, she viewed depth as more important than breadth:

My philosophy is to do less, and do it in more depth, so for me (the analogy activity) is perfectly in accordance with my philosophy. (Anne, biology instructor, interview, March 12, 2003)

Involvement in the analogy exercise was particularly seamless in Anne’s classes. Because she had previously designed a number of small-group activities, her students were well aware of her beliefs regarding the usefulness of this approach. Anne indicated that the small-group nature of the analogy activity made it a good fit for her teaching approaches, and she viewed the analogy activity as an extension of normal practice:

(Working together in groups) was similar to what they do in class with discussions, only carried on to a greater extent, so they had more time (to discuss). I liked that a lot. (Anne, biology instructor, interview, March 12, 2003)

Anne’s students easily adapted to the analogy activity, and I observed that they smoothly moved between their roles as silent listeners and vocal small-group participants, as they formed into the groups they worked with on previous occasions in Anne’s classes.

Sue felt her teaching was driven and constrained by the need to cover large amounts of mandated curricula. She used a lecture-explanation approach in her classes, during which she made use of many teacher-generated analogies, combined with a limited number of small-group activities in which students problem-solved in pairs. Sue did not favor group activities involving larger numbers of students per group, because she worried there would be problems with group members who did not actively participate:

I have a slight aversion to group work, especially in groups of more than two or three, because students complain a lot about people not pulling their weight in the group. (Sue, biology instructor, interview, December 12, 2004)
While Sue’s concerns about the need to cover large amounts of mandated curricula and her views on group size for activities were not congruent with the design of the analogy activity, she still perceived that she benefited from her involvement. Sue acknowledged that trying this strategy with her classes made her question her teaching approach, and her students’ learning:

(The analogy activity) made me re-evaluate what I am doing, and made me look at how students are learning the material. (Sue, biology instructor, interview, December 12, 2004)

Sue’s involvement with the analogy activity prompted a re-evaluation of her teaching practice. This reflection on how her teaching practice impacted student learning is illustrative of metacognition, and is suggestive of conceptual change.

During his classes, Steven, like Sue, routinely used a lecture-explanation approach. However, in his classes students were regularly prompted to demonstrate their understanding by answering questions he posed. Steven indicated that, prior to his involvement with the analogy activity, he had not used small-group activities in class. However, Steven’s interview comments indicate he gained an appreciation of using this student-oriented approach, and realized the value of watching and listening to students’ ideas:

I was surprised by the variety of ideas they (students) came up with. I use a lot of analogies, but I wouldn’t ever have come up with their ideas – they were so off the wall, and while some of them were kind of difficult to follow in the beginning, they all had something to say about (the science concept). One of the really good things was the amount they enjoyed doing it. Some of them were a bit shy, but they all did a real good job and really got into it. You don’t always think that students are going to have much to say, so I enjoyed sitting back and letting them do it, instead of me just doing the same old (thing). (Steven, chemistry instructor, interview, June 19, 2003)

Steven recognized he needed to give up some control during lessons to make his classroom more student-centered, and appreciated the importance of encouraging students to express their ideas. He was surprised that the analogy activity provided him with information regarding students’ understanding of the science:
I know it’s a problem that we have, when students don’t get it in class, and its all way over their heads. Sometimes I can predict where they are going to have problems, so I can go over things really slowly. But it still comes down to this problem of not being able to get into their heads . . . It was good that I was there while they were preparing, because that was when they were working a lot of things out, and they sure didn’t see things quite the way I expected. And then again when they acted them (the analogies) I could see that some of them (the actors) were a bit lost, and the other students had to help them along. (Steven, chemistry instructor, interview, June 19, 2003)

Steven also appreciated how the analogy activity fostered participation of less vocal students, who rarely contributed to classroom discussions:

When I ask them questions, it’s usually the good students that answer, and so I never get to know what the others are thinking, until I ask a question on a test. That was one of the things I liked about doing the analogies – the way I got to see how the students were thinking about things. (Steven, instructor interview, June 19, 2003)

Steven acknowledged the tangible benefits of gaining insight into students’ thinking and encouraging a more relaxed social environment within his classroom. He subsequently indicated he was interested in continuing to use performed analogies within his classroom, and participated (after the study) in such an analogy exercise with another class. Thus, despite his previous lack of involvement with small-group activities, it appears that Steven’s involvement in the analogy exercises encouraged him to make some changes in his pedagogical approach - specifically to move towards making his classroom more student-centered.

Anne, Steven and Sue’s first encounters with student-generated analogies appear to have prompted them to reassess their teaching beliefs and methods. For Anne, who incorporated student-centered activities into her classroom, this reassessment reinforced her teaching beliefs, and she indicated a desire to incorporate similar analogy activities into her classes. Steven and Sue recognized benefits associated with this student-centered activity, and indicated a willingness to change their teaching approaches to accommodate more student-centered learning.
Their responses are consistent with Feldman’s finding (1996), that teachers can evaluate and transform their own knowledge through interaction with students, and by reflecting on their instruction and their students’ understanding.

**Issues that Influence Use of Student-Generated and Performed Analogies**

During post-intervention interviews, both students and instructors commented on a number of issues they saw as influencing the implementation of the student-generated analogy activity in the undergraduate science classroom. Issues mentioned included time constraints, choice of the target concept, students’ content knowledge and preparation, instructional qualities, and assessment.

**Time Constraints**

Nearly half of the students (42%) commented that time restrictions impacted their experience in the analogy activities. Students indicated that fundamental aspects of the analogy activities, such as planning, development and post-performance discussion, were influenced by a shortage of time, and that this limited the learning potential of the activity. Students associated limited time for planning and development with lack of detail and complexity in their analogies:

> Because we had thirty minutes to set it up *(there were)* a lot of the small details we overlooked. Because we were just trying to put something on that we didn’t have time to plan for. *(Linda, biology student, interview, June 19, 2003)*

When pushed for time, groups sometimes took shortcuts that influenced the quality of their product. Fay’s comment illustrates the tension she experienced when their group felt rushed and limited for time.

> We were running out of time, then we had sort of an idea . . . so last minute, someone said okay you just be this and this, and this, but that didn’t make sense
and I said no we can't do that; it doesn't make any sense. (Faye, biology student interview, Feb 11, 2004)

Like their students, the course instructors, Anne, Steven, and Sue, were aware that time restrictions influenced implementation of the analogy activities. Self-imposed time limits resulted from their perceived need to cover large amounts of mandated curricula. All three instructors presented a substantial portion of the curricula using a lecture format, which left little time for other, more student-centered activities. Sue was particularly troubled by the volume of curricula she felt obligated to present:

You are constrained by what has to be presented, because some of the courses I teach have very little flexibility in what (students) have to know when you are done. So, you have to figure out how to present large volumes of material... The problem with introducing enacted analogies into the classroom is time. (Sue, biology instructor, interview, December 12, 2004)

Anne acknowledged that students needed more time (than she had provided) to organize their knowledge of the science concept prior to the analogy activity. When pressed for time some students in Anne’s class represented the complex topic of nuclear control of plant growth with simplistic analogies that did not convey important relationships to the target concept. Anne noticed this and commented:

If you are asking them to bring up knowledge that is not at the forefront of the brain, or things like this that require some integration and deep thought, you need to give more preparation time for (students to read the text and complete assignments), and to get the most out of it. (Anne, biology instructor, interview, February 12, 2004)

Another consequence of the limited time available for the analogy activity was that some post-analogy class discussions were cut short or lacked closure:

We did not have enough time to follow up on it. It would have been useful for the audience to critique it, and say "these are the things we need to follow up on". That would have been a useful exercise. (Anne, biology instructor, interview, February 12, 2004)
These views are consistent with students’ comments, given earlier, indicating that time restrictions limited the learning potential of the analogy activity.

Students and instructors sent a clear message that adequate time is needed if student-centered activities are to be successfully implemented. This call for time is in tension with the existing post-secondary teaching paradigm (Barr & Tagg, 1995) that privileges delivering the mandated curriculum. It was clear that the standardized time block for lecture-based lessons was unsuited to less structured and more open-ended activities, such as analogy performances. This is consistent with Barr and Tagg’s observation that the ‘Instruction Paradigm’, which institutionalizes the 50 minute lecture, is “... antithetical to creating any other kind of learning experience” (Barr & Tagg, 1995, p. 18).

**Choice of Target Concept**

The essence of analogical learning is that the target being represented is conceptually difficult, and therefore may not be completely understood by the analogy developer. However, before a student can generate a meaningful analogy, they must have some understanding of the scientific concept being represented. Thus, selection of the science concept and students’ background knowledge were issues that influenced the quality of students’ analogies. Both students and the instructors had concerns about these elements of the analogy activity. Some students identified their inability to deal with the conceptual complexity, with the result that they generated fairly simple analogies:

I think every one was pretty much at the same level, with the same knowledge. I guess we weren’t going into great depth with the (analogy). (Stephanie, biology student, interview, February 12, 2004)
Anne was aware that complexity of the science concepts she selected could have impacted on analogy development and performances:

Both the concepts we did, the root growth and the immune response, are extremely complex concepts, with a lot of different components, and I wonder if they are too complex to be done like that. (Anne, biology instructor, interview, February 12, 2004)

The choice of complex target concepts may be problematic because an analogy typically allows transfer of a limited number of structural relationships between the analogical model and the target (Zook & Di Vesta, 1991). The difficulty of producing analogical models that represent complex relationships has also been noted by Clement (1993), who has shown that a series of simpler bridging analogies can help students to understand the conceptual relationships being represented. Bridging analogies could become part of a student-generated analogy exercise if the instructor explained their use, and encouraged students to produce a series of simple analogies that represent different aspects of the complex science topic. This, however, would have required more class time be devoted to the analogy exercises. This option was not possible in the present study.

As seen in other studies (Clement, 1989; Nashon, 2003; Pittman, 1999) some of the analogies students developed and performed were simplistic, and did not correspond closely with the target science concept. Anne, Steven and Sue acknowledged this, and attributed these problems to students’ incomplete knowledge of the concept. Sue was particularly concerned that non-majors students needed a solid knowledge base to begin the activity:

(Developing analogies) is hard for non-science majors, even though they were very creative, because they often have trouble with the science concepts... Students need accurate information before starting the analogies. (Sue, biology instructor, interview, December 12, 2004)
Students' Content Knowledge and Preparation for Class

Sue’s concern about students’ knowledge base may have been warranted, as interview comments indicated that for many students, their initial understanding of the target science concept was limited, and this compromised development of analogies. When individual members began the activity with incomplete understanding, the group analogy development process was slow. Another outcome of incomplete background knowledge was that groups produced oversimplified analogies. Students’ suggestions on how to counter this lack of background knowledge tended to focus on the instructor. Some proposed that the instructor needed to be more involved in the initial stages, to help students construct a knowledge base for the science concept:

Even if we had gone through the material just once in class then everyone would have more of a base understanding (of the science concept), to apply that properly. (Carl, biology student interview, March 26, 2003)

Incomplete understanding also appeared to be related to students’ preparation for instruction. Anne expected that students in her two biology classes, as part of their preparation for the analogy activity, would read, and arrive with some comprehension of, the material in their textbooks. During interviews, many of these students (46%) revealed that they either failed to carry out Anne’s assigned reading, or did not benefit from it. Students indicated that their difficulty in learning from textbooks was not limited to Anne’s biology course. Reasons they gave for their problems in learning from the text included the amount of new terminology being introduced for a given topic, and their difficulty in locating material in the text. For some students, the sheer volume of required reading was problematical:

When you are reading 30 pages there is only so much you can assimilate. When you have 2 classes a week and you are reading a chapter before you go to each class it’s absorption. I realize it’s fast paced and that’s how it’s supposed to go, but I’m one of those people (who) have a really bad memory. I can’t read something and remember it. I have to sit down and read something six times. I
think I must have read chapters 1 through 17 in the biology textbook probably three times (a total of 1200 plus pages). (Stephanie, biology student, interview, February 12, 2004)

Part of Stephanie’s problem seemed to be her difficulty in deciphering the relative importance of ideas being presented in the text, and her preference for learning via rote memorization. The illustrations in textbooks were also part of the problem. Diagrams lacked the dimensionality of real-world experience students considered necessary to promote understanding:

... diagrams in the textbook you just look at them and say “okay, that doesn’t help.” They are still photos and that’s not the same as seeing something actually happen. Like, someone can tell you how to drive a car, but actually seeing it done is a totally different thing. I think that can be really helpful. (Vicky, chemistry student, interview, February 12, 2004)

The difficulties that students encountered in text-based learning are problematic because textbooks are the primary learning and teaching resource used in the science classroom (Sanchez & Valcarcel, 1999). Instructors viewed textbook use differently from students, and seemed to be unaware that students had problems learning from texts. After the analogy exercise, Anne commented:

I guess I was expecting them to do it more at a graduate level and to go back and read about the nucleus. Some of them had read about cell types, I saw some students with notes. (Anne, instructor interview, February 11, 2004)

Stephanie was aware of the difference between the expectations of instructors and the performance of students in relation to completion of reading:

I think one of the biggest assumptions of teachers is that they think students do their homework weeks in advance, and they don’t. (Homework) is not due until tomorrow and I haven’t even started. But nobody has, it’s just a huge assumption that people had already researched it because they have done their portfolio, so we should already have the background information... but nobody has done the homework, everyone does it last minute - or most people do. (Stephanie, biology student, interview, February 12, 2004)
This difference between the instructors' expectations and reality with regard to textbook use impacted the level of scaffolding and support provided by instructors, which in turn influenced the outcome of the analogy activity. The fact that differences between instructors' and students' understanding of, and expectations about, the learning process are common (Murray & MacDonald, 1997) suggests that instructors must closely attend to the way students engage in learning, particularly when teaching innovations are being introduced.

**Instructional Issues**

A common theme in students' comments was the need for more specific and detailed directions before the analogies were developed. Students were quite specific. For example, two students indicated that they had difficulty in devising analogy scenarios, and would have benefited from a list of examples:

I think give us certain set scenarios to do it with, or a rudimentary list of ideas. You can think of a million different things after, but when you are asked to think about something, you can't. A list of 10 or 12 different things would give people ideas and allow them to become more creative. (Paul, biology student, interview, March 21, 2003)

Paul's request for illustrative examples as a way to help students to be creative may be related to his experiences in science classes where students are seldom asked to generate ideas. Post-secondary science teaching practices that demand students remember what they have been taught (with little knowledge transformation) may leave students, like Paul, feeling uncomfortable and unprepared when provided with the opportunity to take control of their own learning.

A number of students who devised analogies on plant root growth felt they needed more guidance on what aspects of the target concept should be represented in their analogy:
We thought it was meant to be more focused toward the plant cells, but it wasn’t overly clear how much she (Anne) wanted - but we are in a plant unit right now. (John, Biology student, interview, Feb 11, 2004)

This uncertainty affected the development of the analogies, and the extent to which some analogies corresponded to the target science concept:

We did a project last semester to do with the nucleus, but ... we never talked about that, in the analogy we just talked about the structures and that’s it; and not actually how it all works. (Faye, biology student, interview, Feb 11, 2004)

Faye and John’s comments suggest that the instructor or researcher needs to provide detailed information when introducing an analogy exercise; such information should include emphasizing the importance of mapping shared attributes of the analogy and the target science concept, and clarifying the intended outcomes of the activity.

Twenty one percent of students interviewed suggested that their learning was enhanced when the instructor had input following the analogy presentation. For Pat, who found student-generated analogies to be more memorable than instructors’ analogies, instructor input provided the added benefit of clarifying and validating the analogies:

People my own age are going to relate better to (student-generated analogies than to instructors’ analogies); then that way the teacher can direct where the student has gone wrong. Each of us with a different analogy in the classroom, we’ll probably remember them better, and when the teacher says “I like that idea but it is a little bit wrong here” it’s just going to trigger pathways for me to remember. (Pat, chemistry student, interview June 17, 2003)

Assessment Matters

Whether students valued the analogy exercise, and were willing to put effort into the activity, appeared to be related in part to whether it counted for marks.

Maybe if there had been marks attached to actually coming up with the idea I would have done more. I think if marks were attached to the analysis at the end that would have been good. (Julia, chemistry student, interview, June 15, 2003)
Carl, (a student identified by the instructor as high achieving) suggested that whether work was graded or not helped to determine its status. He commented that lower-status, non-compulsory work would receive less attention when he had to choose between completing different assignments:

... because things aren't graded and aren't compulsory, the amount of effort you are going to get put into pre-knowing the material, or looking into it, or getting ideas, is going to be lessened, I'm no exception. When it comes down to being responsible and choosing what things I'm going to be putting the effort into, the things that aren't compulsory are the first to go. (Carl, biology student, interview, March 26, 2003)

These students' comments illustrate how post-secondary science learning is assessment driven; students see their final grade as the most important learning outcome. This view can lead to students pursuing "knowledge without understanding" (Bodner, 1992, p. 190), a situation that is exacerbated by the current emphasis on testing and standardization within secondary and post-secondary education, which devalues learning outcomes that cannot be directly quantified. The instructors in this study all agreed that it would be beneficial for students to receive marks for their involvement in the activity, but they struggled with the precise nature of evaluation that would best fit the exercise. Despite calls for evaluation procedures to be congruent with the form of instruction (Tobin, Tippins & Gallard, 1994), little information is currently available on how to evaluate undirected, group learning endeavors like the student-generated and performed analogies examined in this study.

Summary of Student and Instructor Messages about Using Student-Generated Analogies

The majority of students enjoyed and valued the analogy activity and saw it as an aid to learning. Enjoyment was related to the social interactions that took place during this student-
centered small-group activity and to the motivational aspect (in contrast to lectures). This type of interactive learning continues to be rare in undergraduate science classrooms, which are dominated by an instructional paradigm (Barr & Tagg, 1995). Enjoyment was also associated with the performative aspect of the activity. The embodied approach to learning made the experience memorable and entertaining, while the novel nature of this pedagogical activity also relieved the boredom and passivity students associated with lecture-based learning.

Students identified a number of different ways in which the analogy activity promoted understanding of the science concept. The visual nature and physical, participatory, aspect of the analogy activity made the learning experience memorable, while the student-generative aspect made the analogies more understandable and meaningful than instructor-generated analogies. The small-group nature of the activity was also important, because it prompted and permitted students to learn from each other. Peer learning was aided when some individuals adopted a teacherly role, and, as students learned from each other, new patterns of communication developed, where assumptions and ideas of class members were more open to discussion and question.

Instructors viewed the analogy activities positively, and identified a number of benefits that the activity provided. They were aware of the increased sense of community amongst students when they worked in small groups. All instructors viewed this increased collegiality favorably, and saw the analogy activity as a way of promoting student interest. Instructors also recognized that the analogy activity provided opportunities for them to gain insights into students understanding of the science concept. In some cases, the performances revealed students’ alternate conceptions, and subsequent discussion of the alternate conceptions in class was an important aid to student understanding.
Despite significant differences in the teaching approaches used by Anne, Sue and Steven, all three instructors viewed the analogy exercise as a good fit with their preferred teaching approaches. Anne had frequently used collaborative small-group activities in her classes, and students easily adapted to the analogy activity. Sue and Steven seldom incorporated small-group activities in their teaching, but were able to incorporate the analogy activity into their classrooms, and students readily accepted this change. For both Sue and Steven, the analogy exercise illustrated the benefits of encouraging a more student-centered classroom.

While both students and instructors viewed the analogy activity as a valuable way of promoting interest and understanding in the post-secondary science classroom, they also recognized and identified ways of enhancing the activity. Both instructors and students were aware that time limitations had a negative impact on the development of the analogies, and identified the need for more time. This presents a dilemma and creates a tension because science instructors typically have mandated curricula that must be taught, and this restricts the time they can invest in new approaches to learning, such as analogy-based learning.

Students commented on the need for more directions and guidance relating to their involvement in the analogy activity. Some students wanted examples of analogies to guide them in devising analogy scenarios. This suggests that further instruction by the researcher on the development and use of analogies might have been useful. Other students wanted more direction regarding what features of the target science concept they needed to represent. This suggests that the instructor could have provided more detailed information on the analogy exercise and its intended outcomes. As the researcher, I could also have ensured that the instructors were more aware of these needs. For other students, learning was enhanced when the instructor had input through discussions following the analogy presentation. This input is important in aiding student understanding, and, as the researcher, I should have stressed this to the instructor.
Both students and instructors were aware that students' prior knowledge of the target science concept influenced the development of meaningful analogies. This highlights the need for the instructor to monitor students' preparation and, as needed, play a more direct role in ensuring that students had sufficient background science knowledge with which to construct analogies.

Some students commented that the effort they were willing to put into a learning activity was related to whether it counted for marks. They viewed their final grade as the most important learning outcome, and did not value activities which were not graded. Instructors noted that, while they wanted to assign grades for the analogy activity, they struggled with the precise nature of evaluation that would fit the activity.

Student and instructor interviews reveal a disjunction between students' views on learning and teachers' views on how they learn. Many students did not complete the textbook readings that their instructors assigned. Some students related this to their difficulty in understanding the material. Others commented that they did not enjoy reading, which may be related to the passive nature of the activity (Dale, 2000).

Suggestions for Implementation of Analogies in the College Science Classroom

Students' and instructors' experiences and perspectives suggest that successful implementation of student-generated and performed analogies in the college science classroom may depend on whether certain conditions are met. Of primary importance is the need for instructors to provide enough time for all aspects of the analogy activity. This need is problematic, because it may conflict with the existing teaching paradigm (Barr & Tagg, 1995), in which covering mandated curriculum is an over-riding concern.
In choosing the science concept for the analogy activity, instructors should consider the complexity of the concept to be taught, and whether students’ have sufficiently well developed background science knowledge to develop meaningful analogies. This attendance to students’ prior understanding fulfils the need for focus described by Treagust, Harrison and Venville (1998) when using the FAR (focus-action-reflection) model for teaching with analogies. Before students devise their analogies, instructors should provide them with direction and guidance on analogy development, including the importance of mapping shared attributes of the analogy and the target science concept. This provides the basis for students to refine and develop their analogies and subsequent performances.

After the analogy performances, instructors and students need to discuss their understanding of the analogies and science concepts, including shared and unshared attributes of the analogy and the target concept. It is also important that instructors discuss with students any alternate science conceptions that are revealed. This provides the reflection on the analogy activity that Treagust, Harrison and Venville (1998) view as important in promoting student understanding.

The above conditions are important in ensuring that instructors provide an environment in which students are able to construct analogies that aid their understanding of difficult science concepts. It is also important that students value the analogy exercise, and are willing to put effort into the activity. This appears to be related to whether their involvement counts for marks. It is therefore important for instructors to develop assessment procedures that evaluate students’ participation in, and the learning taking place through the analogy activities.

In this chapter and the previous one, I have presented my findings on the ways that student-generated and performed analogies can help college students understand complex science concepts, and on students’ and instructors experiences and perspectives on the analogy
exercise. In the final chapter of this dissertation I summarize the important findings, provide my conclusions, and offer suggestions for future research directions.
CHAPTER EIGHT

SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

My research explored whether the use of student-generated and performed analogies, within first-year college science classes, can help students develop more robust understanding of difficult science concepts. I also analyzed the perspectives of students who participated in student-generated and performed analogies and of their instructors to determine whether this approach was valued in the undergraduate science classroom and viewed as pedagogically useful. My analysis of students’ responses to post-intervention probes and examination questions indicated that students did make gains in conceptual understanding of science topics following the analogy activity. Further, student and instructor interview data showed that the analogy activity was viewed as fruitful in providing a classroom environment that enabled learning.

In this chapter I summarize the findings of my research by returning to the questions that are central to it:

1. In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?

2. What are the perspectives of college students and instructors on learning science using performed analogies?

I also discuss the implications of my research findings and make suggestions for future research.
Summary

Research Question 1: In what ways can student-generated and performed analogies help college students to understand complex and abstract concepts in their science courses?

To study the role of student-generated and performed analogies in promoting conceptual understanding, undergraduate science students participated in analogy activities that dealt with a set of science concepts identified by instructors as complex or intellectually challenging. When students had completed their analogy exercises, I assessed their understanding of the selected concepts by analyzing their responses to probe and examination questions. My findings are given below.

Involvement in the analogy exercise was associated with gains in students' conceptual understanding. Students in preparatory chemistry classes who participated in an analogy-generating and performing exercise, showed significantly greater understanding of a science topic (halogen oxidation) than comparison group students, who did not participate in this activity. Biology students also exhibited gains in conceptual understanding (of the body's immune response) after engaging in an analogy-development activity. Students' responses to post-intervention probe questions about the selected science topic indicated enhanced conceptual understanding when compared with their pre-intervention responses.

The ability to transfer knowledge of the analogy's target science topics to novel situations varied for students' performing at different achievement levels. Lower-achieving chemistry students who participated in the analogy development activity exhibited significant gains in conceptual understanding of the science topic, but were unable to transfer their knowledge to novel situations. Higher-achieving students who participated in the analogy activity were better able to transfer their knowledge of the analogy-related science topic to novel situations.
Students exhibited improved understanding when their analogies clearly represented important features of the target and showed close correspondences to the science concept. These students were better able to articulate how their analogies related to the science concept, and exhibited improved understanding of the concept. This understanding was apparent in their responses to probe questions, and during interviews. Students’ understanding of the science concept was limited when their analogies were simplistic and failed to show close correspondences to the target concept.

The role students assumed during the group work leading to the development and performance of analogies appeared to be related to their gains in conceptual understanding. The role played by students in the analogy activity appeared to be significant. Students who were actively involved in the development and performance of analogies were able to articulate how their analogies related to the science topic. However, students’ interest and participation in the analogy exercise was not always enough, and some students who adopted a passive learning approach did not engage intellectually with the science target, and did not develop their own understanding of the topic.

Research Question 2: What are the perspectives of college students and instructors on learning science using performed analogies?

My study, conducted in different preparatory and undergraduate classrooms, illustrates that student-generated and performed analogies can be used to promote a more student-centered environment in the post-secondary science setting, and points towards the usefulness of this approach in encouraging the development of new teacher-student roles for individual students. Student roles were transformed as they worked in small groups on developing and enacting their analogies. It appears that the use of performed analogies can serve as a means of encouraging,
enhancing and changing modes of communication, while providing a more democratic classroom environment that supports the development of new teacherly behavior in some students. I also found that:

Participation in the analogy activity led to enhanced social interaction and a heightened sense of community. Through their participation in the group analogy sessions, students discovered the importance of peer exchange, and the value of building a community of learners. This realization was an epiphany for many students, who had not previously recognized that social interactions could have a significant place in the science classroom and learning environment.

The combination of social and performative elements in the analogy exercise provided a motivational learning experience that was valued by students. This student-centered activity countered the boredom that students associated with lecture-based science classes, and promoted interest and enjoyment. Students were motivated to participate actively in the exercise.

Students viewed the performative nature of the activity as important in promoting understanding. They perceived that the embodied, performative aspects of the analogy activity were important in promoting engagement, which helped motivate their learning. For these students, active physical involvement in the analogy exercise provided new perspectives that helped to clarify the science concepts.

Students' views about the usefulness of the analogy exercise were closely aligned with their preferred learning styles. Students who regarded themselves as visual learners valued the visual nature of the performances, which helped clarify what they did, or did not, know. Other students, who valued a more holistic approach to learning, found that their active embodied involvement in the analogy activity, including its visual nature, provided a variety of different
opportunities for learning science that were closely aligned with their preferred learning approaches.

Most students believed that student-generated analogies were more easily understood than those generated by teachers. Students viewed analogies generated by their peers as being more familiar and accessible, and also believed that they learned more from being involved in their own analogy performance than from watching those of other groups.

Students who participated in the analogy activity adopted new roles within the classroom. Some students (mostly high achievers) assumed a leadership role in the development of the enactments, and were involved in collaborative teaching and learning; these peer tutors were valued as a source of knowledge and support by classmates. In some cases lower-achieving students adopted passive roles, deferring to the views and opinions of their peers. When this occurred new student-teacher dynamics emerged, with some students adopting the teacherly role of developing the analogy, while other students retained the role of passive learners. Passive students were more comfortable with a teacher-centered classroom; they allowed other group members to adopt the role of teacher, and resisted becoming active learners. Thus, the student-centered strategy of generating and performing analogies was not transformative for all students.

Changes in classroom communication patterns were evident. During the intervention, students became engaged in ‘talking to learn’ and were more willing to listen to, discuss, and question each other’s knowledge. This suggests that the analogy activity may have contributed to students participating as more active learners in the science classroom. Instructors provided anecdotal evidence that students continued to be more actively involved in classroom learning after the analogy exercise had been completed.

Instructors responded positively to the use of performed analogies in their classrooms, and recognized the learning opportunities these afforded. All instructors observed an increased
sense of collegiality in their classrooms after students had worked in groups generating and performing their analogies. Instructors noted that the activities around performed analogies appeared to increase student interest, and foster thoughtful dialogue related to the science concept. For two instructors, involvement with the analogy activity promoted a re-examination of their classroom practice, including how they presented material in class, and whether a more student-centered classroom could be fostered. All instructors noticed that alternate and naïve science conceptions were revealed during the enactments. From this they gained insights into the way students were thinking that helped them prepare for follow-up instruction and remediation.

There were a number of issues that both instructors and students perceived as constraining the analogy activity. These included time restrictions, students’ prior knowledge of the science concept, expectations of students and instructors regarding preparation, selection of science concepts and assessment.

Both students and instructors commented that more time was needed for important aspects of the analogy activity. These included instruction on development of analogies, pre-enactment group discussion and post-enactment class discussion. It is apparent that the standardized time block is unsuited to loosely organized and open-ended activities, such as the analogy exercises.

The prior knowledge of some students was insufficiently developed, and compromised analogy development. Some students recognized that they had insufficient background science knowledge to develop analogies that mapped well to the science concept. They considered that the instructor could play a role in helping them to construct a knowledge base for the science concept. Many students did not carry out assigned reading from the text on the science concept prior to the analogy activity. This indicates that:
There is a disjunction between students' views on learning and instructors' views on how they learn. While instructors expected students to have done preparatory reading from the textbook, few students carried out this task. Reasons given by students included difficulty in navigating around textbooks when learning new material, comprehending new terminology, and completing the large volume of required reading.

Students needed more directions and guidance relating to their involvement in the analogy activity. This included further instruction by the researcher on the development and use of analogies, and more guidance by the instructor on what features of the target science concept should be represented.

The complexity of the science concept selected for the analogy exercises can impact analogy development and performances. Some science concepts were extremely complex, and students found that multi-step science processes were difficult to represent with an analogy. This impacted on their ability to produce analogies that mapped well to the science target, and as a result, some students generated fairly simple analogies.

The effort students were willing to put into the analogy exercise appeared to be related to whether it counted for marks. Students viewed their final grade as the most important learning outcome, and indicated that non-compulsory activities would receive less attention than work that was to be marked.
Implications of the Research Study Findings for Teaching and Learning in Post-Secondary Science Classrooms

This study and the points raised here have significant ramifications for post-secondary institutions, where the primary mode of science instruction continues to be the delivery of information through traditional didactic practices. Such practices ignore what research shows - namely that we must give students a greater role in the learning process, and that this role needs to be carefully constructed if we wish to promote deep conceptual understanding leading to application of ideas. To achieve these ends, those who teach science in colleges and universities will need to re-examine and re-construct their practices. An important first step in this process is the provision of evidence that change is warranted and fruitful. Here is where I believe my study, and the work of others who examine student learning in post-secondary science classrooms, can make an important contribution.

In this study, I found that using student-generated analogies with undergraduate science students can provide an environment that inspires students to take ownership of their learning. It is a powerful instructional strategy that can enhance understanding of science concepts. Students' comments indicate that direct involvement in producing their own analogies was important, and seemed to provide a richer experience than simply hearing about an analogy. Students also indicated that participation in analogy performance and the small and large group discussions contributed to their interest and motivation, by making the topic more meaningful and memorable. This involvement in developing analogies can motivate students to become more actively involved in constructing their own understanding. The use of analogies has been shown to provide such motivation by fostering students' interest in the topic (Duit, 1991) and by breaking up the "monotony of lecture" (Orgill & Bodner, 2004). However, my findings suggest that promoting student interest and motivation through active involvement in the analogy...
performance is not enough. To ensure improved conceptual understanding, students must become intellectually engaged with the science concept, and also be able to map relationships between the analogy and the science target. My findings suggest that college students, who have limited experience in using analogies, need more instruction on how to identify correspondences and map relationships between the analog and target. Pittman (1999) has also identified students' lack of experience in analogy development as limiting their abilities to produce and use effective analogies that map well to the science concept.

Both students and instructors viewed the social nature of small-group activities as important, because it increased interest and allowed students to learn from each other. Thus group process in the generation and performance of the analogies appears to play a significant role. This idea is consistent with observations of Hogan (1999) that cooperative small-group learning activities can provide a classroom environment in which student achievement and motivation to learn are encouraged. An important feature of small-group activities is that learning is enhanced when group discussions encourage students to teach others by communicating both what they know and what they don’t know (Duch, 1996; Gall & Gall 1993; Yu & Stokes, 1998; Duncan & Dick, 2000). Students in my study also associated their involvement in small-group discussions with enhancement of community within the class. This building of community should be encouraged, because of the benefits noted by Mlynarczyk and Babbit (2002), indicating that students who are part of a community of learners have an increased chance of success in college courses.

An important finding of this study was that lower-achieving students made significant gains in conceptual understanding following involvement in the analogy exercise. Group process and participation appear to be important in helping low achievers, by increasing motivation and helping them to decipher conceptually difficult topics that would otherwise remain inaccessible.
to them. My findings are in accord with those of Lawson, Baker, DiDonato and Verdi, (1993) who suggest that the use of physical analogues can contribute to students' conceptual understanding by illustrating and clarifying new theoretical concepts. Involvement in the small-group activities also provided lower-achieving students with opportunities to learn from other students. This is an important way for students to construct understanding, and Lundberg (2003), in a study of college students, found that time spent in peer teaching and discussion of science topics was the strongest predictor of understanding. However, it seems that these elements aren't enough. The failure of lower-achieving students to transfer their understanding of the analogy-related science topic to a novel situation is disappointing but reflective of the challenges of promoting conceptual understanding that can be translated into application of ideas. Lawson, Baker, DiDonato and Verdi (1993) suggest that hypothetico-deductive reasoning skill is a factor that enables conceptual change, which can lead to deep understanding. They suggest that while the use of heuristics such as physical analogues can be helpful to students, successful application of the new concepts requires well-developed cognitive skills, including the ability to choose which conceptions should be applied in novel situations. The message seems to be that if we want students to be able to apply scientific concepts to new situations, science instruction should not only be designed to help students acquire deep understanding of science concepts, but should also explicitly focus on helping students develop reasoning abilities, and to learn to apply them to scientific questions.

Advice for Instructors on using Student-Generated Analogies

This study supports the view that how analogies are used may determine whether they are successful in promoting students' understanding. For example, the failure of some groups to produce analogies that showed close correspondence to the target concept suggests that more
instruction on the process of analogy construction is needed. This observation is in accord with findings by other researchers (see e.g. Libarkin & Mencke, 2001), that instructors need to provide students with direction relating to their participation in more student-centered activities.

To benefit from using analogies, students must understand how their analogy relates to the science target. This understanding can be encouraged in a number of ways. The instructor needs to first emphasize the purpose of analogy development, and what the analogies are meant to accomplish. To encourage students to construct meaningful relationships between the analog and target, the instructor should identify important features of the target to be mapped with the analog. After initial analogy development, the instructor could help students to assess and revise their analogies by suggesting improvements that would highlight important relationships between the analogy and the target. Instructors could also encourage students to be more responsible for their ideas, by asking them to produce written explanations of how their analogy maps to the science topic. Instructors’ participation in post-performance analysis and discussion about the analogy, and its relationships to the science target, is also important, because these activities provide opportunities to help students attend to their alternate science conceptions, while providing an opportunity for instructors to assess students’ prior knowledge.

Whether participation in the analogy activity promotes students’ learning is influenced by a number of elements related to the learning ecology of individual students. My findings indicate that these include incompletely developed organizational abilities, reasoning abilities and limited background knowledge of students. I found that students’ background knowledge is impacted by a disjunction between students’ views on learning and instructors’ views on how they learn. While instructors expected students to have done preparatory reading from the textbook, most students either failed to complete these assignments, or gained little understanding from their reading of the textbook. Instructors need to be aware of these problems, and could more closely
monitor students’ organizational abilities, reasoning abilities and prior understanding. They must also be prepared to provide remediation measures to counter these problems.

Because some students do not value activities that will not directly affect their overall grade, instructors need to consider how to assess student involvement in innovative strategies, in ways that explicitly link the activity and assessment (Pittman, 1999). Such strategies may require a shift away from assessment based on whether students produce the ‘right answer’, to consideration of their conceptual understanding. This shift involves instructors moving away from a summative view of evaluation, which emphasizes the importance of what students know, towards a more formative view of assessment in which the how and why of concepts are central.

**Future Directions**

While this study offers quantitative and qualitative evidence that the use of performed analogies can support improved understanding of science concepts in the undergraduate classroom, many issues remain. For example, my finding that some students’ analogies were more successful at promoting understanding than others prompts me to inquire whether group structure can influence learning. This might involve consideration of students’ prior experiences with small-group and performative activities, cognitive abilities, leadership skills and gender.

My finding that some students were unable to map important analogical relationships to the target concept suggests that further research is needed on how to encourage effective mapping. The research of Kurtz, Miao and Gentner (2001) has shown that analogical transfer is improved when students are encouraged to compare the content of different analogies representing the same target, and this approach, whereby understanding of different analogies is
integrated in order to give an overview of the concept being studied, offers rich possibilities for student-generated analogies.

Also, the inability of lower-achieving students to transfer their understanding to new situations indicates an area where further research is needed. Possible approaches that might enhance deeper understanding for these students include the introduction of more formal student-mentoring during the analogy development, and encouraging students to take a more active role in developing their own analogies.

In addition, post-secondary instructors must play a central role in the process of bringing change to undergraduate classrooms. Thus, understanding their experiences is essential, and research is needed that examines the perspectives of instructors regarding the use of performed analogies and other non-traditional instructional practices in the college science classroom. We also need to understand what conditions foster instructors' use of non-traditional instructional practices in college science classrooms. Specifically, we need to investigate instructors' views on how to address the tensions between implementing more student-centered learning activities, such as the analogy exercise, and the need to cover mandated curricula.

Conclusions

This study of student-generated and performed analogies in the college science classroom provides evidence that student understanding of science concepts was enhanced following participation in analogy generating activities. The combination of student-centered small group discussions and active involvement in the analogy performance produced an environment that provoked students to take ownership of their learning.

This research study supports the view that how analogies are used may determine whether they will advance student understanding. Group process in the generation and
performance of the analogies appears to play a significant role by providing a classroom environment in which student achievement and motivation to learn are encouraged. This study indicates that students valued the opportunity to interact with other members of the class in ways that encouraged a sense of community. Further, students found that developing their own analogies made the science more meaningful, memorable and accessible. However, this alone was not enough. To make gains in conceptual understanding, students needed to recognize correspondences between the analogy and the science target, while engaging intellectually with the science concept. It is here where the instructor should play a facilitating role.

The study also shows that instructors recognized the value of the analogy activity, not only because of the improved social atmosphere within the classroom, but also because of the student alternate conceptions that were revealed during the enactments. Thus the analogy activity provided instructors with insights into students’ understanding of the science topic, and created a pedagogical space where alternate conceptions could be discussed in class.

This study identifies a number of elements which limited students’ gains in conceptual understanding. The instructor can address some of these, such as the complexity of the target concept and the organization of the activity. Others, such as students’ background knowledge and reasoning ability, are related to the learning ecology of individual students, while other issues, such as time limitations are associated with an instructional paradigm.

This study illustrates the benefits of introducing student-generated and performed analogies in the undergraduate science classroom. These include promoting a sense of community, improving student motivation, and encouraging conceptual understanding. This study also provides an example of how a student-centered, active and embodied learning approach can be brought into the science classroom. This is important because, in order to bridge the divide between a transmission mode of instruction and a more student-centered classroom,
college science instructors must re-examine and re-construct their practices. An important first step in this process is the provision of evidence that change is warranted and fruitful. Here is where I believe my study, and the work of others who examine student learning in post-secondary science classrooms, can make an important contribution. It is only through such research, which identifies the spaces for student-centered pedagogy, that the existing teaching paradigm, identified by Barr and Tagg (1995) as limiting change in the undergraduate science classroom, will be transformed to a learning paradigm.
REFERENCES


Johnson, D. W., & Johnson, R. T. (1993). Cooperative learning: Where we have been, where we are going. Cooperative Learning and College Teaching Newsletter, 3(2), 6-9.


APPENDIX A

Information Supporting the Analogy Activity in
Anne’s Biology Course for Science Majors, March 2003

Immune Response Terminology

The following terminology has been adapted from introductory biology texts (Avila, 1992; Campbell, 2002; Starr & Taggart, 1992).

The Immune System: consists of all the bodily components that defend us from disease and recognize self from non-self. Specific immune responses can be categorized as either “humoral responses,” in which white blood cells identify an invader by markers on its surface and then form antibodies against it, or as “cell-mediated responses” in which specialized white blood cells attack a particular target. A cell-mediated response is made against cancer cells, mutant, or infected cells and involves activation of T cells and B cells and other cells involved in the immune response. During this process, cells communicate with one another by chemical secretions (such as interleukins) which stimulate rapid growth and division of some white blood cells (B cells, cytotoxic T cells and helper T cells).

Antibodies: are proteins produced by the immune system that can bind to antigens and help to eliminate them.

Antigens: are large molecules that can trigger an immune system response; these are found on the surface of viruses, bacteria, fungi, pollen and other substances that are foreign to the body.

B Cells: are specialized lymphocytes. When antigens stimulate these cells, they are converted into plasma cells that secrete antibodies.

Cytotoxic T cells: are specialized lymphocytes that destroy body cells infected by certain viruses and fungi. They can recognize body cells that display foreign proteins found in viruses etc.

Helper T cells: are specialized lymphocytes that stimulate rapid division of B cells and cytotoxic T cells, stimulating the immune-system response.

Macrophages: are large cells which engulf and destroy invaders or present them to other immune cells (such as helper T cells).
Memory Cells: are some of the B and T cells that after a first exposure to an invader acquire a “molecular memory” which allows a rapid response to another invasion by the same antigen. MHC proteins are surface markers that mark cells as ‘self’ they are found on almost every cell in the body. The body’s B cells and T cells will not attack cells with only MHC markers but they will respond to cells bearing antigens. Suppressor T cells: slow down or prevent immune-system responses. White blood cells (leukocytes) are responsible for immune responses. There are five major types of white blood cells: monocytes, neutrophils, basophils, eosinophils and lymphocytes.
APPENDIX B

Information Supporting the Analogy Activity in
Anne’s Biology Course for Science Majors, February 2004

Information Useful for Understanding the Development
and Growth in a Plant Root Cell

In the root cap or ‘meristem region’ of a plant the nucleus of the cell is instructing the cell to divide again and again, which causes the root cap to grow and older cells to be pushed outwards. The nucleus orders cell division to take place by releasing a chemical messenger (mRNA), this is stimulated by a hormone (auxin) produced in the shoots and stems of the plant. Cell wall production also takes place as new cells are formed. The nucleus also signals cells to grow and elongate and cells can grow upwards of 10 times their original length in this ‘zone of elongation’. As they elongate, cells take on water to maintain their inner pressure, this causes the cells to expand and the tip of the root and the meristem is pushed through the soil.

As the root tip grows the cell nucleus starts to form specialized parts of the cell. If the cell is in the middle of what is considered to be future vascular tissue, the cell wall is modified to increase its ability to adhere to water. The cell then undergoes programmed cell death, where the cell and its organelles are eaten from within by enzymes produced by the plant itself. A hollow shell is left, which is connected to other cells to form a continuous pathway for transportation of water and minerals to the developing root cells.

All these processes are controlled by the nucleus of each cell, which affects which genes are transcribed to RNA (a nucleic acid/large molecule) and hence what is sent out into the cytoplasm for templates for protein synthesis. Thus different proteins are produced as needed by the cells depending on the cells function and activity. While the nucleus controls the activity of the cell, it is controlled by the type and concentration of hormones around it. Receptors in the cell walls are activated by plant hormones, which send chemical messengers into the nucleus and bind with the DNA. This causes genes to be either activated or inactivated which in turn decides which proteins are manufactured by the cell (Campbell, 2002).
Descriptions of Performed Analogies

The analogies designed by students to illustrate the nuclear control of root growth are briefly described in Table B.1.

Pre-Analogy Question

*It is possible to experimentally separate the three different zones in a growing plant root tip (Portfolio #3 diagram), grind each zone individually and then perform tests (assays) to determine what molecules are present in each zone. Assays that reveal specific mRNAs present in each zone indicate which genes are active in each zone. Such tests show that some mRNAs are present in all three zones, whereas some mRNAs are unique to individual zones.*

Explain the following mRNA data in terms of specific gene activity:

1. All 3 zones contain mRNA from genes that code for ATPase.
2. The root cap contains mRNA from genes that code for DNA polymerase.
(Marks not allocated)

For the development and growth in a plant root cell no post-analogy intervention questions were used.
Table B.1. Student-Generated Analogies (nuclear control of root growth).

<table>
<thead>
<tr>
<th>Analogy Theme</th>
<th>Analogy Description and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Growing Company</td>
<td>A manager (<em>cell nucleus</em>) of a growing company interviews prospective workers (<em>cells</em>) for different departments. Each worker describes their skills and attributes, such as getting nutrients, transporting goods and bringing in energy by basking in the sun. Each person is hired by the manager, who notes that he is building a strong company.</td>
</tr>
<tr>
<td>Paper Airplane</td>
<td>Paper airplanes are thrown out from a central character to different individuals (<em>mRNA being sent from a central nucleus to modify and build a cell</em>). On receiving the paper airplane, the first individual pushes group members off chairs. A second group member receives a paper airplane and stacks the chairs. Other group members receive paper airplanes, move the stacked chairs, move the tables and turn the tables on their sides. Each gives the paper airplane back to the central character after completion of their task. Finally, a paper airplane is sent from the central character to one of the group members. This results in the member blowing a horn and all group members throw out small balloons at the audience.</td>
</tr>
<tr>
<td>Messages (No narration)</td>
<td></td>
</tr>
<tr>
<td>The Meristem Kingdom</td>
<td>King Nucleus tells his people (<em>different cells</em>) to go out and prosper, divide and repopulate, spread out and elongate. The king tells his subjects to specialize and help the empire grow strong and prosper. He points to each individual in turn and asks him or her what role they can play. Each person replies, describing their specialization, such as dungeon master, garbage remover and artist.</td>
</tr>
<tr>
<td>Pirates</td>
<td>The head pirate (<em>cell nucleus</em>) tells his sailors to fight (<em>representing cell division</em>). While they are fighting with sticks, they say that they are being cut up and are reproducing. The head pirate asks for his servant (<em>mRNA</em>) and he tells his crew to spread out and fetch drinks (<em>representing plant roots spreading out for water</em>).</td>
</tr>
</tbody>
</table>
Mitosis and Meiosis Terminology

The basic terminology relating to cell structure and function was covered during the second week of the course, but the details of cell division relating to meiosis and mitosis were taught during the fifth week when the intervention was carried out. The following terminology, pertinent to a discussion of meiosis and mitosis, has been adapted from introductory biology texts (Avila, 1992; Campbell, 2002; Starr & Taggart, 1992).

A **Chromosome** consists of one long strand of DNA coiled around proteins, it can be single or double stranded. Chromosomes are found in homologous pairs. Humans have 46 chromosomes per cell, which occur as 23 pairs (22 somatic and 1 sex).

**Centromere** is the point of attachment of the two chromatids.

**Chromatids** are the two structures making up a replicated chromosome.

**DNA** (deoxyribonucleic acid) is contained in the nucleus of the cell in the form of chromosomes it contains many genes (that give directions for making proteins).

**Homologous Chromosomes** are two chromosomes of the same type, one comes from the mother and one comes from the father.

**Nucleolus** a specialized structure in the nucleus formed from various chromosomes and active in the synthesis of ribosomes (ribosomes are cell organelles active in protein synthesis).

**Nucleus** a component of eukaryotic cells that contains the cell’s genetic material and is enclosed by a double membrane (the nuclear envelope).

**Sex cells** are **haploid** (with only one of each pair of homologous chromosomes that were present in the parent cell) and have 23 chromosomes.

**Sister Chromatids** are two identical chromosomes that are held together by their centromeres.

**Somatic cells** are **diploid** (2 homologous chromosomes of each type) and have 46 chromosomes.

**Spindles** are structures formed out of microtubules that orchestrate chromosome movement during cell division.
Telomeres are the ends of chromosomes.

The above terminology is useful for discussing cell replication, which is important for growth, repair and reproduction (single celled organisms). For cell replication to occur a eukaryotic cell must grow and make additional organelles, enzymes, etc., and it must duplicate its DNA, separating its DNA into two and dividing into two cells (cytokinesis). Cells divide in two ways either by mitosis or meiosis, I will consider each of these in turn and then the similarities and differences between them.

**Mitosis** is a process of cell division (in cells with a membrane-enclosed nucleus and membrane-enclosed organelles) that occurs in plants, fungi, protists and animals. It is the basis of bodily growth and of asexual reproduction in some situations. Nuclear division during mitosis ensures that the parental number of chromosomes is maintained in daughter cells. Mitosis is divided into the growth phase (interphase) and four stages: prophase, metaphase, anaphase and telophase.

- **Prophase**: chromatin condenses, the nuclear envelope disappears and the nucleolus disappears.
- **Metaphase**: chromosomes line up along the equator of the cell. Spindle fibres attach to the centromeres of the chromosomes.
- **Anaphase**: centromeres separate and sister chromatids move to opposite ends of the cell. Telophase I: the nuclear envelope reforms around each set of chromosomes, the nucleolus reappears, and the chromosomes uncoil into their chromatin forms. The nuclear membrane reforms around each new parcel of chromatin to form 2 new nuclei. This is followed by cytokinesis, during which the cells split resulting in the production of two daughter cells, each having the same genetic components as the original parent cell and the chromosome number remains constant.

**Meiosis** is a type of cell division that only occurs in the formation of the gametes – the sex cells (or germ cells). Its purpose is to produce reproductive cells. During meiosis the parental chromosome number (46) is reduced by half (23). It consists of the following stages:

- **Interphase**: DNA is duplicated.
- **Prophase I**: homologous chromosomes pair, chromatin shortens and thickens to become chromosomes, the nuclear envelope disappears and the nucleolus disappears.
Metaphase I: homologous chromosomes line up in pairs along the equator of the cell. Spindle fibres attach to the centromeres of the chromosomes.

Anaphase I: separation of homologous chromosomes.

Telophase I: chromosomes arrive at the poles of the cell, the nuclear envelope reforms in some cells. Each cell has one of each homologous chromosome, cytokinesis occurs, the cells split forming two daughter cells with half as many chromosomes as the parent cell.

Prophase II: chromosomes shorten and thicken, the nuclear envelope disappears.

Metaphase II: chromosomes line up along the equator of the cell. Spindle fibres attach to the centromeres:

Anaphase II: centromeres divide, sister chromatids separate and become chromosomes.

Telophase II: the nuclear envelope forms around each set of chromosomes. A nucleolus appears in each nucleus. The chromosomes lengthen and cytokinesis occurs forming 4 daughter cells each having half as many chromosomes as the other body cells.

Descriptions of Performed Analogies
The analogies designed by students to illustrate mitosis and meiosis are briefly described in Table C.1.

Pre- and Post-Analogy Question

Pre-Analogy Question:
List the similarities and differences between mitosis and meiosis (10 marks).

Post-Analogy Questions:
Compare and contrast mitosis and meiosis. Be specific in describing the results of these processes and chromosome movement. DO NOT describe each phase (12 marks).
<table>
<thead>
<tr>
<th>Analogy Theme</th>
<th>Analogy Description and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpretative Dance Class (Meiosis)</td>
<td>A narrator describes the steps involved in meiosis while other group members perform a dance routine. Group members move apart and together when the narrator says that the chromosomes move apart and together. They throw out scarves when the narrator mentions the spindles forming. Other dance moves are performed as the narrator describes telophase, metaphase, the formation of daughter cells etc.</td>
</tr>
<tr>
<td>The Four Seasons (Mitosis)</td>
<td>The four seasons are used to represent the four stages of Mitosis. In winter (prophase) students move around holding a blue paper and a red paper (cells). In spring (metaphase), they line up in a row. In summer (anaphase) they pair up and face each other, and in fall (telophase) they use 2 blue and 2 red papers to illustrate cell division and the production of daughter cells.</td>
</tr>
<tr>
<td>Café Meiosis</td>
<td>The different phases of meiosis are depicted as a nine-course meal using various arrangements of coloured ribbons and straws (chromosomes) on a plate. The food on plates is moved around (representing the chromosome movement and the centrioles) as each course is presented to a student sitting at a table. One plate is cut into two halves and the food redistributed between them. The student says that she would like enough for her 4 children at home, so the process of dividing the meal is repeated.</td>
</tr>
<tr>
<td>The Fairy Tale (Meiosis)</td>
<td>The story of the chromosome family line-dancing at the spindle saloon is narrated, while group members illustrate the story using straws as finger puppets (chromosomes) together with printed signs (showing different phases of meiosis). A dispute breaks out at the spindle saloon, forcing the separation of the family members. They go to opposite poles and are then separated by an earthquake. They regroup and start a new life in a new cell and live happily ever after.</td>
</tr>
<tr>
<td>Balloons (Mitosis)</td>
<td>Mitosis is depicted using balloons (as the cell) with the chromosomes drawn on them. A large orange balloon with chromosomes drawn on the surface is held up to represent interphase. When reversed it represents prophase. We are told centrioles start to appear which are shown on the balloon. Metaphase is shown as a blue net with pink and green paper chromosomes and bows for centromeres lined up at the equator. The chromosomes are then separated into 2 pairs. Daughter cells form (telophase) shown with small orange and yellow balloons.</td>
</tr>
</tbody>
</table>
Scoring Criteria for the Pre- and Post-Intervention Questions

Student responses to the pre and post-intervention questions were scored by Sue based on the following criteria (shown in tables C-2 and C-3):

Table C.2. Differences Between Mitosis and Meiosis

<table>
<thead>
<tr>
<th>Mitosis</th>
<th>Meiosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Involved in formation of body cells</td>
<td>Involved in formation of gametes (sex cells)</td>
</tr>
<tr>
<td>Produces 2 daughter cells genetically identical to the mother cell.</td>
<td>Produces 4 daughter cells genetically non-identical to the mother cell and each other.</td>
</tr>
<tr>
<td>Consists of only one nuclear division</td>
<td>Consists of two nuclear divisions M-I and M-II</td>
</tr>
<tr>
<td>Number of chromosomes present in the mother cell is maintained in both daughter cells (diploid number maintained).</td>
<td>Daughter cells contain half as many chromosomes as the mother cell (diploid number of chromosomes is reduced to haploid number).</td>
</tr>
<tr>
<td>Daughter cells are similar to each other and also to the original mother cell</td>
<td>Daughter cells differ from each other as well as from the original mother cell.</td>
</tr>
</tbody>
</table>

Table C.3. Similarities Between Meiosis and Mitosis

<table>
<thead>
<tr>
<th>They both go through the four phases of Mitosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Both divide and produce daughter cells</td>
</tr>
<tr>
<td>Both are a form of reproduction</td>
</tr>
<tr>
<td>Both go through cytokinesis and the nuclear envelope is broken down and formed again in daughter cells</td>
</tr>
<tr>
<td>In both processes the chromosomes replicate and condense, the nucleus disappears and centrioles and spindles are formed.</td>
</tr>
<tr>
<td>In mitosis all chromosomes line up along the equator of the cell during metaphase and the same happens in meiosis during metaphase I and metaphase II.</td>
</tr>
<tr>
<td>DNA replication occurs in both during interphase.</td>
</tr>
<tr>
<td>Centrioles replicate in prophase of mitosis and prophase I of Meiosis</td>
</tr>
</tbody>
</table>
Kinetic Molecular Theory (KMT) is used to explain the behaviour and properties of gases. It is based on a number of assumptions for an ideal gas (in reality there is no ideal gas, but real gases approach ideal behaviour under certain conditions of temperature and pressure). The assumptions of KMT are as follows:

1. Gases consist of submicroscopic particles (molecules).
2. Most of the volume occupied by a gas is empty space, as the gas molecules are widely spaced apart and do not attract one another.
3. Gas particles are in constant motion and move in straight lines in all directions. They collide frequently with one another and with the walls of the container.
4. All collisions are perfectly elastic, no energy is lost or gained when gas particles collide with each other or with the walls of the container.
5. The average kinetic energy for gas particles is the same for all gases at the same temperature and its value is directly proportional to the temperature of the gas in degrees Kelvin.

Based on this theory if the temperature of a gas in a container is increased, the kinetic energy and velocity of the particles increases and the number of collisions increases. This would result in an increase in pressure (due to the gas particles colliding with the walls of the container more frequently) unless the volume of the container is increased proportionately to the temperature (Hein & Arena, 2000).

Descriptions of Performed Analogies

The analogies designed by students to illustrate the behaviour of gas molecules are briefly described in Table D.1:
Table D.1. Student-Generated Analogies (behaviour of gas molecules).

<table>
<thead>
<tr>
<th>Analogy Theme</th>
<th>Analogy Description and Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid, Liquid and Gas</td>
<td>To begin, the group members are close together in fixed positions (<em>molecules in a solid ice cube</em>). A red cloth is waved over the group (<em>heat is added</em>) and the people move around more while still close together (<em>molecules in a liquid</em>). The red cloth is waved again, and people move further apart (<em>gas molecules in random motion</em>). The group members release small balloons, which deflate and shoot around the room.</td>
</tr>
<tr>
<td>Kinetic Corner</td>
<td>Group members move around, tossing balloons in the air and batting them with their hands (<em>gaseous hydrogen atoms in random motion</em>). The members move closer together and continue to bat the balloons with their hands. The narrator (<em>Raggedy-Anne</em>) indicates that the gas molecules are now in a smaller container, producing more collisions with the walls and an increase in pressure. A red cloth is waved (<em>gas sample is heated</em>). The balloons are tossed around even more rapidly (<em>increased temperature increases velocity of the molecules, producing more collisions per second, and an increase in pressure</em>).</td>
</tr>
<tr>
<td>Gas Molecules Moving Between</td>
<td>Part of the room is sectioned off with tables, to form two separate areas, with the group members moving around within one of these areas (<em>gas molecules in random motion within a container</em>). The narrator indicates that the temperature has been increased and the group members move more rapidly, bumping into each other more often. One table is removed so that the group members can move from one area to the other (<em>gas molecules escaping through random motion</em>). The group members who escaped into the new area move more rapidly than when they were in the smaller space (<em>gas molecules appear to be moving more quickly because they have more space</em>).</td>
</tr>
</tbody>
</table>


**Pre- and Post-Analogy Questions**

Steven used two pre-analogy questions, adapted from Nussbaum (1985), and Nurrenbern and Pickering (1987).

**Pre-Analogy Question #1**

The following diagram represents a cross-sectional area of a steel tank filled with hydrogen gas at 20°C and 3 atm pressure. (The dots represent the distribution of H₂ molecules).

Which of the following diagrams illustrate the distribution of H₂ molecules in the steel tank if the temperature is lowered to -20°C?

![Diagram Options]

**Pre-Analogy Question #2**

The pressure in a flask containing gas molecules was decreased using a vacuum pump:

Which of the eight diagrams best represents the molecules of gas before and after pressure was decreased?

![Diagram Options]
**Post-Analogy Questions #1 and #2**

These were the same as the pre-analogy questions given above.

**Post-Analogy Question #3**

The equation of state of a gas gives the relationship between a number of variables: 

\[ PV = nRT \]

(a) What is the relationship between pressure and temperature, if the volume of a sample of gas is kept constant?

(b) Show how this relationship between temperature and pressure is consistent with the assumptions of the kinetic molecular theory of gases.

**Scoring and Coding Criteria for Pre- and Post-analogy Questions**

**Scoring Criteria for Pre and Post-Analogy Questions #1 & #2**

Every written response for multiple choice questions #1 & #2 was scored. A correct response was scored as 1 and an incorrect response was scored as 0.

**Coding Criteria for Question 3(b) Relating to Kinetic Molecular Theory**

Every written response for part 3(b) of the final exam question was coded using a one point system that corresponded to meaningful reference by the student to random motion of gas molecules. Responses that failed to mention either random motion or velocity of molecules were coded as zero.
APPENDIX E

Information Supporting the Analogy Activity in

Steven’s Preparatory Chemistry Course, May 2004

Information About the Relative Oxidizing Power

of the Halogens (Fluorine, Chlorine, Bromine and Iodine)

The halogen topic is taught as an extension of a unit on periodic trends. Four key concepts, taught in class, are important to the understanding of periodic trends, and are central to an explanation of relative oxidizing power:

1. Oxidation involves the loss of electrons. The species that is oxidized loses electrons, while the oxidizing agent, which is reduced, gains the electrons. Oxidation-reduction thus involves a transfer of electrons.

2. Size of the outer electron shell typically increases for elements going down a group in the periodic table. The distance of the outer electrons from the nucleus therefore increases for elements going down a group in the periodic table.

3. The attraction between the oppositely charged nucleus and electrons will diminish with increased distance of separation.

4. The attraction exerted by the nucleus on outer electrons can be rationalized by use of the term ‘effective nuclear charge’, which is calculated by considering the combination of (i) the attraction from the nucleus experienced by the outer electrons and (ii) the repulsion (‘shielding’) experienced by the outer electrons due to interactions with inner electrons.

In simple terms, effective nuclear charge is considered to increase from left to right in a row of main group elements across the periodic table, but to remain constant for elements within a group (i.e. column) in the periodic table. When comparing the oxidizing ability of halogens, where all the elements are in the same chemical group, effective nuclear charge can be considered as remaining constant for the different elements, but the relative ability of atoms to attract electrons will vary as the size of atoms changes. Thus a small atom, such as fluorine, would be expected to exert a stronger attraction on an outer electron than a large atom such as iodine, and the reaction

\[ \text{F}_2 + 2 \text{I}^- \rightarrow 2 \text{F}^- + \text{I} \]
which involves a transfer of electrons from the iodide ions to fluorine atoms, would be expected to occur.
APPENDIX F

Interview Questions

Student Interview Questions

The following represent some of the questions that students were asked in post-intervention semi-structured interviews:

1. How did you like doing this activity?
2. What value did you see in participating in this way?
3. What did you learn about your understanding of the (science) concept?
4. Do you think this is a good way to learn science, why or why not?
5. What do you value as a teaching/learning approach in the science classroom?
6. What does understanding mean to you?
7. Do you prefer teacher-generated or student-generated analogies?
8. How would you describe this activity to a friend wishing to take the course- would you suggest they try this? Why?
9. Did the group interaction, or the physical involvement, or interacting with the ideas, help you to understand the science concept?
10. What did you learn from doing this with your group?
11. When do you think this kind of activity should be done?
12. When you were watching the performed analogies were you able to assess which were more accurate? (Please explain).
13. After watching the tape students were asked:
   a) What were you trying to do here? Did you think it worked?
   b) What did this ‘action’ show about ‘the science concept’? Why did you decide to do that?
   c) What was it indicating?
Instructor Interview Questions

The following represent some of the questions that instructors were asked in post-intervention semi-structured interviews:

1. What do you think are the pros and cons of using student-generated performed analogies?
2. Do you consider that this is a good way to learn science?
3. Do you think that participating in the analogy activity has changed your views on teaching?
4. Do you think that participating in the analogy activity has changed your views on how students learn science?
5. Do you have any suggestions for changes to the analogy activity that would improve it?
6. Did you observe any alternate conceptions when students performed their analogies?
7. What do you consider your role is as an instructor?
8. In what ways do you think your students learn in class?
9. If you could teach first year science classes in any way that you wanted, with no restrictions on cost, time, or anything else, how would you teach them?
10. What do you consider your most important resource is as an instructor?
11. What do you think the most important thing is that a student should have gained from your (biology) class?
Certificate of Approval

Principal Investigator
Mayer-Smith, J.

Department
Curriculum Studies

Institution(s) Where Research Will Be Carried Out
Univ of Victoria

Co-Investigators
Spier-Dance, Lesley, Education

Proposed Title
Perspectives on the Post-Secondary Science Classroom: Enacting Science Through History, Media, and Models

Approval Date
MAR 13 2003

Term (Years)
1

Documents Included in This Approval
March 2, 2003, Version 2, Consent forms / Jan. 12, 2003, Questionnaires

Certification
The protocol describing the above-named project has been reviewed by the Committee and the experimental procedures were found to be acceptable on ethical grounds for research involving human subjects.

Approval of the Behavioural Research Ethics Board by one of the following:

Dr. James Frankish, Chair,
Dr. Cay Holbrook, Associate Chair,
Dr. Joe Belanger, Associate Chair

This Certificate of Approval is valid for the above term provided there is no change in the experimental procedures.
# Certificate of Approval

**Principal Investigator:** Mayer-Smith, J.  
**Department:** Curriculum Studies  
**Institution(s) Where Research Will Be Carried Out:** Univ of Victoria  
**Co-Investigators:** Spier-Dance, Lesley, Education  
**SPONSORING AGENCIES:**  
**Title:** Perspectives on the Post-Secondary Science Classroom: Raising Science Through Analogies and Models  
**Approval Renewed Date:**  
**Term (Years):** 1  
**CERTIFICATION:**  

The protocol describing the above-named project has been reviewed by the Committee and the experimental procedures were found to be acceptable on ethical grounds for research involving human subjects.

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Dr. James Frankish, Chair,  
Dr. Cay Holbrook, Associate Chair,  
Dr. Susan Rowley, Associate Chair

This Certificate of Approval is valid for the above term provided there is no change in the experimental procedures.