AN EXPLORATION OF COMPUTER-SIMULATED EVOLUTION AND SMALL GROUP DISCUSSION ON PRE-SERVICE SCIENCE TEACHERS’ PERCEPTIONS OF EVOLUTIONARY CONCEPTS

by

Ronald Douglas Macdonald

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Department of Curriculum, Teaching and Learning
The Ontario Institute for Studies in Education of the University of Toronto

© Copyright by Ronald Douglas Macdonald 2000
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author’s permission.

L’auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L’auteur conserve la propriété du droit d’auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-46623-X
AN EXPLORATION OF COMPUTER-SIMULATED EVOLUTION AND SMALL GROUP DISCUSSION ON PRE-SERVICE SCIENCE TEACHERS' PERCEPTIONS OF EVOLUTIONARY CONCEPTS

Ronald Douglas Macdonald

Doctor of Philosophy

Department of Curriculum, Teaching and Learning
University of Toronto
2000

Abstract

The primary goal of this study was to explore how the use of a computer simulation of basic evolutionary processes, in combination with small-group discussions, affected Intermediate/Senior pre-service science teachers’ perspectives of basic evolutionary concepts. Qualitative and quantitative methods were used in a case study approach with 19 pre-service Intermediate/Senior science teachers at an Ontario university.

Several sub-goals were explored. The first sub-goal was to assess Intermediate/Senior pre-service science teachers’ current conceptions of evolution. The results indicated that approximately two-thirds of the participants had a poor understanding of basic evolutionary concepts, with only 2 of the 19 participants demonstrating a strong comprehension. These results were found to be very similar to comparable samples of subjects from other research. The second sub-goal was to explore the relationships among Intermediate/Senior pre-service science teachers’ understanding of contemporary evolutionary concepts, their perspectives of the nature of science, and their intentions to teach evolutionary concepts in the classroom. Participants’ knowledge of evolutionary concepts was found to be associated strongly with their intentions to teach evolution by natural selection ($r = .42$). However, knowledge of evolutionary concepts was not found to be associated with any particular science epistemology perspective. The third sub-goal was to analyze and to interpret the small-group discussions as members interacted with the simulation. The simulation was found to be highly engaging and a very effective method of encouraging participants to speculate, question, discuss and learn about important evolutionary concepts. Analyses of the discussions revealed that the simulation evoked a wide array of correct conceptions as
well as misconceptions. The fourth sub-goal was to assess the extent to which creating a lesson plan on the topic of natural selection could affect Intermediate/Senior pre-service science teachers' conceptions of evolutionary theory. All of participants' lesson plans contained various types of misconceptions related to natural selection and overestimated what could be accomplished in a 70 minute period.

The results are discussed with respect to the importance of prior knowledge, the influence of cognitive biases in learning evolutionary concepts and the role of computer simulations in obviating biases inherent in traditional curriculum materials used for teaching evolution.
Acknowledgments

To the 19 members of the class of 99 who participated in this study: may your enthusiasm, dedication, curiosity, and love of education benefit your students the way it has benefited me. Thank you. Without you, this thesis would not have been possible.

To Erminia Pedretti: you graciously permitted me time and access to your students, patiently guided my thinking and have strongly influenced my views on what science is, how it is practiced and what it means to teach.

To Derek Hodson: you have challenged me to think more clearly and critically about the scientific enterprise. You helped me to earn the “Ph” in front of the “D”.

To Rina Chohen and Dong Galbarith: you provided me with insightful comments and criticisms and helped me to improve the final product to meet your standards of excellence.

I would also like to thank the following for reading drafts and allowing me to bounce an endless stream of thinking and babbling off them: Norm Himel, Alex Lawson, Chris Frank, Randy Penfield, and Ruth Lewis.

Many thanks to Paul Fairlie and Jim Rising, my content experts, for their assistance in refining my instruments and helping me to think more clearly about complex issues.

I am indebted to my in laws, Mike and Anne Santolupo who provided support and encouragement at every opportunity.

Finally, Sil, my love, your patience, tolerance, wisdom and optimism made this journey a delight.
### Table of Contents

Abstract ........................................................................................................... ii
Acknowledgements ....................................................................................... iv
Preface ............................................................................................................. xv

**Chapter 1 - Learning about Evolution: The Challenges**

A Context for the Problem ................................................................. 1
Goals of the Study and Research Questions ............................................ 3
Understanding Evolution: Conceptual Challenges ............................... 4
Understanding Evolution: Epistemological Issues .................................. 12
Perspectives on the Nature of Science ..................................................... 26
Intentions to Teach Evolution by Natural Selection ............................... 27
Summary ..................................................................................................... 31

**Chapter 2 - The Computer: A Tool for Learning**

Computers in Education: An Overview ............................................... 34
Computers in the Classroom: Epistemological Perspectives .............. 35
Simulations as Cognitive Tools for Learning in Science ....................... 38
Summary ..................................................................................................... 47

**Chapter 3 - Method**

Overview ..................................................................................................... 49
Participants ................................................................................................. 49
Study Phases and General Design Rationale ......................................... 51
Surveys and the Simulation ................................................................. 52
   Evolutionary Knowledge Survey (EKS) .............................................. 52
   Nature of Science Survey (NOSS) .................................................... 55
   Intentions to Teach Evolution Questionnaire (ITEQ) ....................... 57
   Resources Used Survey (RUS) ......................................................... 57
The Simulation ............................................................................................ 58
Procedure ................................................................................................. 59
   General ............................................................................................... 59
   Phase 1 - Administer Questionnaires, Form dyads/triads ................. 59
Chapter 3 - Method (cont'd)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Simulation for Familiarization</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>Lesson Plan</td>
<td>63</td>
</tr>
<tr>
<td>4</td>
<td>Simulation for Exploration</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>Concept Map</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Final Interviews</td>
<td>68</td>
</tr>
</tbody>
</table>

Chapter 4 - Results: Questionnaire Data

<table>
<thead>
<tr>
<th>Overview</th>
<th>Knowledge of Evolution</th>
<th>Intentions to Teach Evolution</th>
<th>Perspectives on the Nature of Science</th>
<th>Knowledge and Intentions</th>
<th>Knowledge and Perspectives on the Nature of Science</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Chapter 5 - Results: The Simulation Discussions

<table>
<thead>
<tr>
<th>Overview</th>
<th>Phase 2 - Using the Simulation</th>
<th>Phase 2 - Unit of Selection Question</th>
<th>Phase 4 - General</th>
<th>Phase 4 - Question One</th>
<th>Phase 4 - Question Two</th>
<th>Phase 4 - Question Three</th>
<th>Phase 4 - Question Four</th>
<th>Phase 4 - Question Five</th>
<th>Phase 4 - Question Six</th>
<th>Supplemental Findings</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Chapter 6 - Results: Analyses of Participants' Understanding of Evolution

<table>
<thead>
<tr>
<th>Summary</th>
<th>Lesson Plans</th>
<th>Concept Maps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 10: Educational Implications

Educational Implications ............................................................................... 243
Limitations of the Study .............................................................................. 243
Considering Science Pedagogy ................................................................. 246
Concluding Remarks .................................................................................. 247

References ................................................................................................... 252
List of Tables

Table 1. Number of 1st and 3rd year Pre-service Science teachers who provided Darwinian, Lamarckian or Other type of responses to questions regarding evolutionary phenomena ........................................ 11

Table 2. Nonscientific beliefs examined in 954 non-major biology students ...... 19

Table 3. Important factors related to conceptual difficulties in understanding evolutionary concepts .................................................. 32

Table 4. Principles for designing computer-based cognitive tools for learning and problem solving .......................................................... 37

Table 5. Five criteria of a good scientific model that can be used in describing the nature of a computer simulation ........................................ 41

Table 6. Phases of the study conducted over a 13 week period, a brief description of the activities associated with each phase, and the focus or questions addressed at each phase .................................................. 51

Table 7. Descriptions of Nott and Wellington's (1993) five dimensions as assessed on their Nature of Science Survey ........................................ 56

Table 8. The dialogue and question used in the analysis of group discussions in phase two of the study ........................................ 63

Table 9. The questions used in phase four of the study to promote group discussions ............................................................................. 66

Table 10. Percentage of participants who answered each of the 20 EKS questions correctly arranged from highest percentage correct to lowest percentage correct ........................................ 70
Table 11. Mean and standard deviations of Intention component scores for participants in the low and high intention groups ............................................73

Table 12. Percentage of participants (n = 19) who responded to each item for a given VOSTS question ........................................................................74

Table 13. Epistemological categories for each of the 20 VOSTS items ..........74

Table 14. Means, standard deviations and ranges for participant scores on the five dimensions of the Nott and Wellington (1993) "Nature of Science" scales ........................................................................77

Table 15. Number of participants categorized by knowledge of evolutionary concepts (low, high) and intentions to teach evolutionary concepts (low, high)..........................................................78

Table 16. Participants' mean scores and standard deviations for items on the three intention components as a function of their knowledge-intention category ............................................................79

Table 17. The means, standard deviations and difference scores for items that comprise the "Attitude" dimension of the ITEQ scale as a function of low intention/low knowledge (LL) group and the high knowledge/high intention (HH) group .........................................................81

Table 18. VOSTS questions where the LL and HH groups differed in number of respondents by more than 33%..................................................82

Table 19. Means and standard deviations for the five dimensions of the Nott and Wellington (1993) "Nature of Science" scales as a function of participants' scores on the EKS (high and low) .................83
Table 20. The average number of words uttered by each participant for all six questions combined as a function of group size (dyad/triad) and EKS distribution score (bottom, middle, and upper third) ........................................................................................................................................153

Table 21. The themes that emerged from participants' discussions about the simulation and questions answered during phase two and phase four ........................................................................................................................................157

Table 22. The definitions of natural selection provided by the groups who included one in their lesson plans........................................................................................................................................161

Table 23. The percentage of participants (n=19) whose answers to two applied questions about the evolution of a trait in a species were considered Darwinian, Lamarckian or Other........................................171

Table 24. Percentage of participants who ranked a given information resource most useful as a function of their EKS category (low - high) ........................................................................................................................................174

Table 25. Percentage of participants who ranked a given activity most useful as a function of their EKS category (low - high).............................175
List of Figures

Figure 1. The Theory of Planned Behaviour ............................................................... 28

Figure 2. Self-reported number of full-time university biology courses for all 19 participants as a function of declared principal teachable subject ........................................................................................................... 50

Figure 3. An example of a "gene" graph used by participants when answering the questions in the manual. This gene graph illustrates the percentage of surviving Red and Black ants with different Strength genes for sampled times ...................................................... 62

Figure 4. A concept map created by P10 showing her perceptions of the relevance of natural selection in evolution ................................................................. 155

Figure 5. A concept map categorized as "conceptually vague" created by P13 ......................................................................................................................... 164

Figure 6. A concept map categorized as "conceptually vague" created by P17 ......................................................................................................................... 165

Figure 7. A concept map categorized as containing a "saltation" misconception created by P8 ........................................................................................................ 166

Figure 8. A concept map categorized as containing a "Lamarckian" misconception created by P9 ........................................................................................................ 167

Figure 9. A concept map categorized as containing a "causal order" misconception created by P1 ........................................................................................................ 168

Figure 10. A concept map categorized as containing a "level of selection" misconception created by P6 .......................................................................................... 169
Figure 11. A concept map categorized as containing a "level of selection" misconception created by P2..........................................................170

Figure 12. A summary of the possible factors influencing one's intentions to teach evolution by natural selection .........................207

Figure 13. The importance of teacher's knowledge in teaching mathematics .........................................................................................208

Figure 14. The concept map contained in the resources provided to participants ........................................................................250
List of Appendices

Appendix A. Evolution Knowledge Survey .......................................................... 262
Appendix B. Nature of Science Survey ................................................................. 276
Appendix C. Intentions to Teach Evolution Questionnaire .................................. 288
Appendix D. Resource Use Survey .................................................................... 298
Appendix E. MicroAnts Simulation: Manual ......................................................... 300
Appendix F. Letter of Informed Consent ............................................................... 314
Appendix G. Debriefing Information .................................................................. 316
Appendix H. Evolution by Natural Selection: Concept Map ............................... 317
Appendix I. Final Interview .................................................................................. 319
Preface

The theory of evolution by natural selection is currently the only scientific theory which can account for the diversity, unity and function of life on the planet. One would expect that because of this theoretical status it would be widely adopted, well understood and taught openly at all three levels of education. This is not the case. Only about 9% of people polled believe in contemporary evolutionary theory (Coben, 1994). The educational literature reveals pervasive misunderstandings of evolution that are difficult to change (e.g., Bishop & Anderson, 1996, Brumby, 1984). Moreover, the theory tends to be actively avoided by students and teachers (e.g., Zuzovsky, 1994) and is, at times, the subject of outright hostility by the general public and academics alike (National Academy of Sciences, 1998; Gould, 1999). As Gould (1999) noted:

... we should cringe in embarrassment that, at the dawn of a new, technological millennium, a jurisdiction in our heartland [Kansas] has opted to suppress one of the greatest triumphs of human discovery. Evolution is not a peripheral subject but the central organizing principle of all biological science. No one who has not read the Bible or the Bard can be considered educated in Western traditions; so no one ignorant of evolution can understand science (Gould, 1999, p. 39).

The primary goal of this study was to explore how the use of a computer simulation of basic evolutionary processes in combination with small-group discussions affected Intermediate/Senior pre-service science teachers' perspectives of contemporary evolutionary concepts. In order to accomplish this primary objective, several sub-goals were established. These were to: 1) assess Intermediate/Senior pre-service science teachers' current conceptions of evolution, 2) explore the relationships among Intermediate/Senior pre-service science teachers' understanding of contemporary evolutionary concepts, their conceptions of the nature of science, and their intentions to teach evolutionary concepts in the classroom, 3) analyze and to interpret the small-group discussions as members interacted with the simulation, and 4) assess the extent to which the standard practice of creating a lesson plan about natural selection could affect Intermediate/Senior pre-service science teachers' conceptions of evolutionary theory.

Several specific research questions were examined. The first question of interest addressed whether this group of Ontario Intermediate/Senior pre-service science teachers had a level of understanding of evolutionary concepts similar to the levels of
understanding reported in the literature for comparable samples of subjects (e.g., Brumby, 1984; Zuzovsky, 1994). Second, could Intermediate/Senior pre-service science teachers' knowledge of evolutionary concepts aid in the prediction of their intentions to teach evolution by natural selection? The third question was related to participants' perspectives on the nature of science. Specifically, would individuals who endorsed a "positivist" view of science have higher scores on a test of evolutionary knowledge when compared to participants who endorsed a more "relativist" view of science? Last, would using a computer simulation of basic evolutionary processes, in combination with small-group discussion, be an effective way to reveal the nature of Intermediate/Senior pre-service science teachers' conceptions of evolution?

The thesis is organized into 10 chapters. Generally, Chapters 1 and 2 cover a review of the relevant literature. Chapter 3 details the methods of how the study was conducted. Chapters 4, 5 and 6 focus on the results of thesis. Chapters 7, 8 and 9 provide a discussion of the results. Chapter 10 examines some of the educational implications of the study.

Specifically, Chapter 1 reviews the literature pertaining to the conceptual and epistemological perspectives on teaching and learning evolutionary concepts. Chapter 2 provides an overview of computers and their use as an educational learning tool. Chapter 3 covers the methodological aspects of the study including a description of the participants, the instruments used in the study and the details of the six phases of the investigation.

Chapter 4 covers the results pertaining to the questionnaire data collected in the study (see Table 6, p. 51). Chapter 5 provides a qualitative analysis of the small group discussions that took place during participants' use of the computer simulation (see Table 6, p. 51). Chapter 6 discusses both the quantitative and qualitative data that explored participants' knowledge of evolutionary concepts as it relates to the processes of: 1) developing a lesson plan on natural selection, 2) creating a concept map of major evolutionary constructs, and 3) answering applied questions about basic evolutionary processes. In addition, data pertaining to participants' perspectives on the resources used in the investigation, their views on the use of the computer simulation as a tool for understanding evolutionary concepts, and their solicited final comments on any aspects of the study per se, are presented in Chapter 6 (see Table 6, p. 51).
Chapter 7 is a discussion of the results generated by the questionnaire data. Chapter 8 is a discussion of the qualitative findings that arose from participants' use of the simulation. Chapter 9 is a discussion of the quantitative and qualitative data that explored participants' knowledge of evolutionary concepts and their personal views on study.

Finally, Chapter 10 examines some of the educational implications that arose from the quantitative and qualitative data gathered during the study. Included in this last chapter is the recommendation for an immediate and comprehensive review of how evolution is taught in the Ontario school system.
Chapter 1
Learning About Evolution: The Challenges

If I were to give an award for the single best idea anyone has ever had, I'd give it to Darwin, ahead of Newton, and Einstein and everyone else. In a single stroke, the idea of evolution by natural selection unifies the realm of life, meaning, and purpose with the realm of space and time, cause and effect, mechanism and physical law (Dennett, 1995, p. 21).

A Context for the Problem
On July 1, 1858, Alfred Wallace and Charles Darwin made a joint presentation to The Linnaean Society of London regarding how the diversity of biological form emerged in natural populations of organisms (Gribbin & Gribbin, 1997). Then, in November, 1859, Charles Darwin published the first of several editions of the now famous, *On The Origin of Species*. In the time since the publication of this book, no other theory in the history of science has created such controversy or generated such research interest (Dennett, 1995; Hellman, 1998; Horgan, 1996; Nickels, Nelson & Beard, 1996).

Yet, despite the fact that Darwin's theory is now more 140 years old, polls, tests, and research consistently show that approximately two-thirds or more of individuals studied exhibit difficulty in understanding, and explaining contemporary evolutionary concepts (Bishop & Anderson, 1990; Brumby, 1984; Zuzovsky, 1994). Given the centrality of evolutionary theory to biology and other areas of life (e.g., understanding the emergence of drug resistant diseases, explaining the extinction of species, eradicating genetic diseases, selective breeding of plants and animals), this number is alarmingly high.

Educational research aimed at exploring the various difficulties students have in understanding evolutionary concepts is relatively new, due primarily to the fact that, in North America, there has been a strong legal and political "chill" on teaching evolutionary concepts in public schools. For example, not until 1968, in the case of Epperson v. Arkansas, did the U.S. Supreme Court invalidate an Arkansas state law that prohibited the teaching of evolution. Over the years, numerous similar cases have been brought before the courts (National Academy of Sciences, 1998). More recently, in 1987, the U.S. Supreme Court, (i.e., Edwards v. Aguillard) invalidated a Louisiana statute that prohibited the teaching of evolution in public schools, except when it was taught alongside of creation science. This case, now known as the "Edwards Restriction" (i.e.,
evolution does not have to be taught concomitantly with creation science), has not prevented a steady stream of legal challenges attempting to prevent the teaching of evolutionary concepts in public schools (National Academy of Sciences, 1998).

It is important to be clear on the implication this legal context has had on teaching and learning of evolutionary concepts in classrooms: as recent as 30 years ago, not only was Darwin's theory not being taught in US public schools, it was illegal to do so. Simply, the paucity of research that explores why students have problems understanding evolutionary concepts is partly due to the fact that these concepts have been prohibited by law from even appearing as a part of the US public school science curriculum. This legal climate has had a strong influence on creating a equally chilly political atmosphere throughout North American public schools. For example, the only place that there is a reference to the word “religion” in the entire 23 page document outlining Ontario's new grades 9-12 high school science curriculum for 1999 and into the new millennium is in the grade 12 unit dealing with evolution.

During the last 15 years, some progress has been made in introducing evolutionary concepts into public school science classrooms. However, there is still some question among educational researchers and teachers regarding how difficult it is for students to understand contemporary ideas of evolution. Ridley (1996) suggested that evolution by natural selection is, “A beautifully simple and easily understood idea” (p. 3). Gribbin and Gribbin (1997) noted that “… natural selection ensures that individuals best fitted to their environment reproduce most effectively in their turn, and leave more offspring. That’s all there is to it” (p. 51). Dennett (1995) argued,

To put it bluntly but fairly, anyone today who doubts that the variety of life on this planet was produced by a process of evolution is simply ignorant -- inexcusably ignorant, in a world where three out of four people have learned to read and write. Doubts about the power of Darwin’s idea of natural selection to explain the evolutionary process are still intellectually respectable, however, although the burden of proof for such skepticism has become immense, ... (p. 46).

In stark contrast with these assertions about the ease with which contemporary evolutionary ideas can be understood is a growing body of literature that points to just the opposite conclusion. The purpose of this chapter is to examine some of the conceptual
and epistemological issues that students and teachers face when trying to learn contemporary evolutionary concepts.

**Goals of the Study and Research Questions**

Polls, tests, and research consistently show that approximately two-thirds or more of the individuals studied exhibit difficulty in understanding, explaining and believing contemporary evolutionary concepts (Brumby, 1984; Hellman, 1998). Given the centrality of evolutionary theory to biology and to other areas of life (e.g., understanding the emergence of drug resistant diseases and agricultural pests, explaining the extinction of species, eradicating genetic diseases), this number is alarmingly and, arguably, dangerously high. One critically important group that is essential in helping to correct this situation but has not received much research attention is pre-service science teachers.

The primary goal of this study was to explore how the use of a computer simulation of basic evolutionary processes in combination with small-group discussions affected Intermediate/Senior pre-service science teachers’ perspectives of contemporary evolutionary concepts. Several sub-goals were also examined. One sub-goal was to assess Intermediate/Senior pre-service science teachers’ current conceptions of evolution. A second sub-goal was to analyze and to interpret the small-group discussions as the members discussed the simulation. This examination was conducted to see if the views Intermediate/Senior pre-service science teachers’ had about the simulation revealed any patterns or insights regarding their conceptions of contemporary evolutionary concepts. A third sub-goal was to explore the relationships among Intermediate/Senior pre-service science teachers’ understanding of contemporary evolutionary concepts (see Appendix A), their conceptions of the nature of science (see Appendix B), and their intentions to teach evolutionary concepts in the classroom (see Appendix C). The last sub-goal was to assess the extent to which the standard practice of creating a lesson plan (i.e., on natural selection) could affect Intermediate/Senior pre-service science teachers’ conceptions of evolutionary theory.

Several research questions were also examined. The first question was: Does this group of Ontario Intermediate/Senior pre-services science teachers have a level of understanding of evolutionary concepts similar to the levels of understanding reported in the literature for comparable samples of subjects (e.g., Brumby, 1984; Zuzovsky, 1994)? The second question was: Can Intermediate/Senior pre-service science teachers’
knowledge of evolutionary concepts aid in the prediction of their intentions to teach evolution by natural selection? The third question was related to participants’ perspectives on the nature of science. Specifically, would individuals who endorsed a “positivist” view of science have higher scores on a test of evolutionary knowledge when compared to participants who endorsed a more “relativist” view of science? The last research question addressed in this study was, would using a computer simulation of basic evolutionary processes in combination with small-group discussion be an effective way to reveal the nature of Intermediate/Senior pre-service science teachers’ conceptions of evolution?

Understanding Evolution: Conceptual Challenges

One of the earliest investigations that explored students’ conceptual difficulties with evolutionary concepts examined first year Australian medical students’ understandings of natural selection (Brumby, 1984). One hundred and fifty students (approximately 18 years of age) participated in the study and a sub-sample (n=32) took part in structured interviews. The main intervention of the study involved: 1) having subjects provide written responses to problems based on the concept of natural selection prior to a course on medical biology, 2) course instruction that, in part, covered natural selection as it relates to the practice of medicine, and 3) having subjects answer one question that required the application of the concept of natural selection on a year-end exam. In the structured interviews, subjects responded to additional problems based on natural selection in which they were asked to “think aloud” as they provided answers.

In evaluating the written responses, Brumby found that subjects’ apparent understanding of evolutionary concepts depended on the type of question asked. For example, approximately two-thirds of subjects responded with the correct Darwinian answer when the question asked them to explain increasing insect resistance to the effects of a pesticide. However, when subjects were asked to explain why scientists had concerns about doctors over-prescribing antibiotics, only 14% of subjects provided a Darwinian explanation. In the structured interviews, only one-third of subjects (n=11) mentioned that both the insecticide problem and the antibiotic problem involved the concept of natural selection.

Overall, Brumby reported that just three of the 32 students interviewed were identified as having a good understanding of natural selection. Of the 18 students who
reported studying Biology in high school, 15 had "only partial or poor understanding" of evolutionary concepts (p. 499). Subjects' performance on the final examination question were similarly poor. Only about a third of the 150 students in the study were able to articulate correctly how natural selection applied to medical practice. These findings are particularly disconcerting because they imply that even a cursory understanding of genetics and its relationship to evolutionary concepts was not being attained by these high school students. Moreover, these results were evident despite students having received lectures designed specifically to help them with understanding how natural selection applied to medicine.

In trying to account for the results, Brumby (1984) speculated that students leave high school with much more than simple errors in their knowledge base of ideas related to natural selection. Instead, students were reasoning, incorrectly, that organisms were able to change important characteristics related to survival volitionally and that these changes could be passed on to progeny. This explanation is the same as that offered by Jean Baptiste Lamarck and others nearly 180 years earlier (Mayr, 1982; Ridley, 1996). Thus, students leave high school using the same Lamarckian reasoning regarding the emergence of phenotypic characteristics in a population that is no different from the reasoning applied to the problem at least two centuries earlier.

A brief aside is necessary because it is important to be clear about what is meant by "Lamarckian reasoning". First, before pointing out where Lamarck's ideas went astray, it is a worthwhile historical tribute to point out what he got right.

Lamarck also offered the best theory of the mechanism of evolution that anyone could come up with at the time, but there is no reason to suppose that, if the Darwinian theory of mechanism had been around at the time, he would have rejected it. It was not around, and it is Lamarck's misfortune that, at least in the English-speaking world, his name has become a label for an error -- his theory of the mechanism of evolution -- rather than for his correct belief in the fact that evolution has occurred (Dawkins, 1991, p. 289, original emphasis).

The Lamarckian mechanisms for how evolution occurs are twofold: 1) the principle of use and disuse, and 2) the inheritance of acquired characteristics. The principle of use and disuse argues that as organisms interact with their environment, the mere fact they are using parts of their body enables them to improve or to enhance their opportunities for survival. In other words, organisms have direct, volitional control over
all aspects of their survival by merely using the traits that they possess. The second Lamarckian mechanism presumes that effects of use and disuse for a given trait are inherited. That is, the characteristics that are acquired during the lifetime of the organism are passed on to offspring. The classic example that is often used to illustrate both Lamarckian mechanisms in operation is the giraffe's long neck. The story goes that as a population of giraffes consumes foliage in the lower branches of a grove of trees, a need to reach higher into the canopy to obtain food would emerge. This need results in giraffes having to strive for their food by straining to reach it in the higher branches, thus stretching their necks in the attempts. The act of using their necks to stretch for food results in giraffes having longer necks. This longer neck, acquired via the need to use it for gathering food, is passed on to offspring and, therefore, offspring are born with slightly longer necks than their parents.

As Dawkins (1991) pointed out, Lamarckian theory has great emotional appeal. It places control for survival squarely within an organism's capabilities. All that is required for an organism to survive is for it to exert some willpower and effort by using those traits it possesses. Then, not only will the organism prosper but the organism's offspring will benefit too; there are no losers in the Lamarckian game of life. Lamarck's ideas are simple, intuitive, apparently easy to observe and experience in nature, and fit nicely with the way most Homo sapiens live their daily lives. Unfortunately, to date, despite assiduously bona-fide and fraudulent attempts to find evidence for Lamarck's mechanisms of evolution, his ideas have received no scientific support (Dawkins, 1991). Yet, as discussed next, the fact that the scientific community no longer accepts Lamarck's ideas does not mean that the reasoning Lamarck applied to describing evolutionary phenomena died with him.

The purposes of discussing Lamarckian reasoning are twofold. First, it is the single most obvious and consistent misconception that students have regarding evolutionary concepts (Bishop & Anderson, 1990; Demastes, Good & Peebles, 1995a; Demastes, Settlage & Good, 1995b; Jensen & Finley, 1995; Jensen & Finley, 1996; Lawson & Thompson, 1988; Smith, Siegel, & McInerney, 1995; Zuzovsky, 1994). Second, it is so ubiquitous, both historically and currently, that Lamarckian reasoning itself and how it is applied, not just to evolutionary concepts but to other phenomena in nature as well (Paulos, 1988), may reveal something about our cognitive architecture (Cosmides & Tooby, 1994).
Parenthetically, the second point raises the ironic possibility that *Homo sapiens* may not have evolved the kinds of reasoning/perceptual apparatus that allow for recognizing the tacit processes and counter intuitive mechanisms that underlie evolution (Deacon, 1997). Specifically, learning about and understanding how a process like evolution by natural selection operates will not be easy because, like many phenomena in science, it is counter intuitive (Wolpert, 1993). Counter intuitive means that it will be difficult for our "primitive" brains to take the standard input we receive from the world about the phenomenon, process that input, and then immediately and easily arrive at an accurate conception of the processes responsible for producing the respective output.

Another seminal and important study conducted by Bishop and Anderson (1990) attempted to understand the conceptual difficulties students face in learning evolution by natural selection. The subjects in their investigation were 110 college students enrolled in a nonmajors' introductory biology course that included specific instruction on evolutionary concepts. Although these students did not have biology as a major, 93% reported that they had at least one or more years of study in biology. In the investigation, students were asked to provide explanations on a pretest to questions such as, "Cave salamanders are blind (they have eyes which are non-functional). How would a biologist explain how blind cave salamanders evolved from sighted ancestors?" (Bishop & Anderson, 1990, p. 418, original emphasis).

Results from the pretest revealed that more than two-thirds of students held conceptions that were not accepted scientific explanations despite the students' own beliefs that they had a good understanding of evolution by natural selection. Answers provided by subjects to explain characteristics such as non-functional eyes in salamanders included ideas related to "needs of the organism", "use and disuse", (both Lamarckian-type explanations) and an incorrect application of the term adaptation (Bishop & Anderson, 1990, p. 422). Moreover, the researchers found no relationship between the number of previous biology courses taken and the level of students' conceptual understanding.

In their study, Bishop and Anderson (1990) used course material that was:

... geared toward producing conceptual change. Using principles of conceptual change learning, we attempted to develop instructional materials, including lecture overheads, laboratory activities, and problem sets that would result in students: (a) becoming dissatisfied with their existing conceptions, (b) achieving minimal understanding of the scientific
conception, and (c) seeing that the scientific understanding is useful and plausible in a variety of situations (cf. Anderson & Roth, in press; Posner, Strike, Hewson, & Gertzog, 1982). The materials we developed (Bishop & Anderson, 1985) presented students with various situations which called for the application of natural selection principles. Student understanding was contrasted with scientific theory and the flaws in student understanding was [sic] discussed (p. 424-425).

It is important to note that this model of conceptual change (Posner, Strike, Hewson, & Gertzog, 1982) makes the critical first assumption (see point 'a' above) that students in fact have an existing conceptual "framework" for understanding the phenomenon in question. Furthermore, this assumption implies that such frameworks are sufficiently well developed and supported with evidence to a degree that would allow for some kind of comparative analysis to take place among competing alternatives. As discussed briefly below, and in more detail in the next section, this assumption does not appear to be valid when it comes to the kinds of preconceptions students have about evolutionary concepts.

Bishop and Anderson (1990) suggested that one of the main conceptual difficulties students appeared to have was in associating the effects of two independent processes (random mutation and nonrandom selection), with the emergence of species-specific, functionally adaptive characteristics in a population of organisms. Paradoxically, it appears that it is the deceptively simple means by which natural selection operates that creates problems for many learners. That is, the difficulty for most learners appears to arise in not being able to separate the product (functionally complex adaptations) from the process (a simple series of iterated algorithmic events that occur over protracted periods of time) that produces them. On the one hand, there are two interdependent processes, that in principle, are not much more operationally complex to understand than the kind of rule-driven algorithm used by most 5th graders to do long-division. On the other hand, there are the marvelously complex adaptations (e.g., products of the process such as the eye) that are apparent in the world around us. As Bishop and Anderson noted, students believed that "it would be much simpler if organisms could simply acquire those features necessary for survival but nature does not operate this way" (p. 427). As noted earlier, a question that has gone unexplored in this educational domain is why students use Lamarkian reasoning at all.
Bishop and Anderson (1990) concluded that evolution by natural selection was a concept “more difficult for students to grasp than most biologists imagine” and that “even revised teaching methods and materials, however, were not sufficient to help a significant number of students” (p. 425). Thus, even after students had taken a course the researchers believed addressed the important and difficult issues related to learning the concepts of evolution, only about 50% of their subjects showed improved posttest scores.

As noted above, there is some question regarding the degree to which students have any kind of rudimentary knowledge framework for evolutionary concepts. McClelland (1984) provided a notable caveat about using the term “framework” to describe students’ conceptions of scientific phenomena. For McClelland, a framework implies an interconnected set of ideas and thoughts that can be used together to help control, understand, predict and explain a given concept. Frequently, students use ad hoc, disconnected and altogether incorrect notions as part of their explanatory “framework” for natural phenomena. As discussed in the next section, this appears to be the case with students' conceptions of evolutionary concepts (Demastes et al., 1995a; Demastes et al., 1995b).

The idea that some students may have little in the way of intricately connected explanatory propositional networks for some scientific concepts was evident in Strike and Posner’s (1992) modifications to their model of conceptual change (Posner et al., 1982). Changes to their original model were in response to criticisms that their theory did not accurately capture the nature of prior knowledge students can have about a given science concept. As a result, they expanded their description of prior knowledge to include the idea that: “Conceptions and misconceptions can exist in different modes of representation and different degrees of articulateness. They may not exist at all but may easily appear to do so,...” (Strike & Posner, 1992, p. 162, my emphasis). As Bishop and Anderson (1990) discovered, the nebulous and often non-existent prior knowledge of evolutionary concepts that students possessed was, in part, responsible for the relatively poor level of concept attainment. This outcome resulted despite a well planned and comprehensive compensatory curriculum. Thus, when students have nothing more than an ad hoc, perfunctory “framework” for a scientific phenomenon, they may tend to rely on an intuitive form of reasoning to explain it. Students' preconceptions of evolutionary events as observed by Bishop and Anderson (1990) seem to correspond with this conclusion.
As noted above, what still remains to be answered is why Lamarckian reasoning, and not some other reasoning form, is the default type of intuitive thinking most consistently applied by students to explain evolutionary phenomena. This question is even more interesting because, relative to the parsimonious, simplistic, and algorithmic nature of natural selection, Lamarckian conceptions of evolution require some tortuously complex details and untenable twists of logic to work (Dawkins, 1991; Ridley, 1996). In contrast, Darwin's evolutionary process is an inherently simpler mechanism than Lamarck's. Any individual capable of doing long division is in fact applying a problem solving approach identical in form to the process of natural selection (Dennett, 1995). So, there is nothing about the concept of evolution by natural selection per se that should create any insurmountable problem for students.

A less obvious problem that emerges when relying on students' ideas as the starting point for conceptual change is that a teacher must first perceive a discrepancy between a student's conception and the contemporary scientific explanation before any attempts at remediation can occur. As will be discussed next, in order for teachers to perceive of a conceptual disparity between what students understand about a scientific concept and what they know about the same phenomenon, teachers themselves must have a firm conceptual grasp of the material. For pre-service science teachers, it appears that their understanding of evolution by natural selection can be quite poor.

The results of research concerning pre-service science teachers' understanding of evolution by natural selection are no more encouraging than those obtained for medical (Brumby, 1984) or biology (Bishop & Anderson, 1990) students. Zuzovsky (1994) administered a pretest of evolutionary concepts to pre-service science teachers who were either in the first or third year of study in a science pedagogy course. Zuzovsky describes the third year as, "... the year when they [student teachers] complete their pedagogical studies and most of their science courses, including an advanced course in genetics. Most of them are students who specialized in biology in high school and studied the topic of evolution" (Zuzovsky, 1994, p. 559). The pretest was given to a sample of first year students and to two separate samples of third year students. The pretest included open-ended questions such as, "When they were first sold, insecticides were highly effective in killing flies and mosquitoes. Today, some 20 years later, a much smaller proportion of these insects dies when sprayed. Explain why you think this is so" (Zuzovsky, 1994, p. 569). Students' responses were coded as "Lamarckian", "Darwinian" or "Other".
The results of Zuzovsky’s study are presented in Table 1. The scores indicated only small differences among student responses in different years of the program and between students in the same year of the program. The most prominent response type was Lamarckian. In other words, like the subjects in Brumby’s (1984) and Bishop and Anderson’s (1990) studies, students used “needs of the organism” as their primary causal explanation for evolutionary events. When students were asked to reflect on the reasons for the disparity between their conceptions and contemporary scientific evolutionary ideas, they suggested that “it was much harder to change subconscious beliefs and values than to achieve conceptual change” (Zuzovsky, 1994, p. 565). Zuzovsky did not elaborate on precisely what students meant by “subconscious beliefs and values” but they were apparently involved in the development and maintenance of students’ own conceptions of evolution. Given the influence that these beliefs and values appeared to have for Zuzovsky’s students, a closer examination of the nature and effect these factors have on students’ conceptions of evolution is warranted.

Table 1.
Number of 1st and 3rd year Pre-service Science teachers who provided Darwinian, Lamarckian or Other type of responses to questions regarding evolutionary phenomena (Modified from Zuzovsky, 1994).

<table>
<thead>
<tr>
<th>Year of Pre-Service Program</th>
<th>Response Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Darwinian</td>
</tr>
<tr>
<td>1st year (n = 13)</td>
<td>2</td>
</tr>
<tr>
<td>2nd year (Sample 1) (n = 14)</td>
<td>3</td>
</tr>
<tr>
<td>3rd year (Sample 2) (n = 16)</td>
<td>4</td>
</tr>
</tbody>
</table>

Zuzovsky’s (1994) approach to remediating the misconceptions held by this sample of students was to have them reflect on the responses they gave in the pretest, and then to discuss similarities and differences between their answers and current scientific ideas of evolutionary biology. Unfortunately, there is no mention of how group discussions operated (e.g., the size of groups, the kinds of preparatory activities, content of the discussions), nor does Zuzovsky report any follow-up data regarding student progress towards a more accurate understanding of evolutionary concepts. To appreciate better how, and if, conceptual change occurs under such remediating circumstances, a more structured analysis of what transpires during group interactions is required.
Taken together, the research by Brumby (1984), Bishop and Anderson (1990) and Zuzovsky (1994) suggests that despite students' participation in biology courses designed to help them learn evolutionary concepts, a significant majority fails to acquire accurate contemporary scientific understanding of evolutionary theory. As the pedagogical role of high school science teachers shifts from the view that teachers are didactic purveyors of knowledge to the view that teachers are facilitating knowledge building, it is important that pre-service science teachers (who will be responsible for teaching evolutionary concepts) have the requisite knowledge required for this role. In other words, to be an effective facilitator requires, as a minimum, a reasonably sound understanding of the science principles under investigation. This is especially true because contemporary science education has begun to rely more heavily on student-student discussions to advance understanding in a particular domain. Thus, teachers must not only know the subject matter well, but in addition, they must know how to structure groups appropriately, understand the kinds of interactions that could take place in such a context, and anticipate the kinds of reasoning that students could exhibit during discussions in order to maximize opportunities for learning. In other words, a teacher must have strong pedagogical content knowledge (Shulman, 1986).

In summary, despite a relative lack of research regarding the conceptual difficulties that students and teachers have in understanding evolutionary concepts, investigations have revealed the following: 1) the majority of students have significant misconceptions regarding the processes of evolution by natural selection, 2) students' preconceptions of evolutionary concepts are nebulous, intuitive, and/or non-existent, 3) standard compensatory curricula are consistently less effective than anticipated, 4) students appear to use an ubiquitously common reasoning error (Lamarckian) when attempting to explain biological phenomena and processes, and 5) beliefs and values are suspected to influence students' knowledge of evolution but the nature of this influence remains unexplored.

Understanding Evolution: Epistemological Issues

Lamarckian-type answers provided by subjects in the studies noted earlier (i.e., Bishop & Anderson, 1990; Brumby, 1984; Zuzovsky, 1994) appear to be remarkably consistent with responses offered by subjects in other investigations in this domain (Demastes et al., 1995a; Demastes et al., 1995b; Jensen & Finley, 1995; Jensen & Finley,
Broadly, a significant majority of answers provided by subjects can be categorized into the following conceptual themes which are inconsistent with scientifically accepted ideas: Lamarckian; anthropomorphism/anthropocentric; and teleological (purposeful design) (Jensen & Finley, 1996). This convergence on a relatively small set of alternative conceptions to explain evolutionary events offers support to McClelland’s (1984) suggestion that, for most people, many physical phenomena have little relevance for them. That is, of all the events and natural phenomena that individuals encounter in their lives on a daily basis, most are neither particularly salient nor important. As such, a coherent scientific framework for understanding such events is simply unnecessary; there is no reason to construct any deep theoretical framework to guide one’s actions or thoughts, or to help one understand those phenomena. Thus, when individuals are confronted with a researcher asking questions about a particular scientific phenomenon to which most have never given much thought, it is reasonable to expect that some simple, intuitively obvious, common sense, and superficially accessible form of causal reasoning would emerge in their answers.

A corollary to McClelland’s (1984) ideas suggests that the extent to which evolutionary phenomena can be made personally salient and important may raise the cognitive and emotional stakes for individuals to the point where a more active process of knowledge building and integration could follow. One immediate example of how this might be accomplished is in the area of rising drug resistance among diseases that are likely to affect students’ lives. There are many basic evolutionary concepts involved (as well as social and political processes), for example, in the emerging tuberculosis epidemic, or in HIV, meningitis, and influenza outbreaks which are perhaps more poignantly and personally relevant. Yet, raising personal relevance in an attempt to motivate students to be more active and engaged with a topic is likely to be only part of the solution. Other factors, ones which are less open to external intervention, appear to be operating against educating students about evolution by natural selection.

Is there a way to account for the kind of convergence in the form and content of superficial reasoning that individuals use in explaining evolutionary concepts both in contemporary research and historically? Resnick (1996) has offered one reasonably parsimonious idea that he called a tendency towards the “centralized mindset” (Resnick, 1996, p. 257). He suggested that people have difficulty in seeing that apparently
complex phenomena can occur as a result of very simple processes. For example, "Too often, when people observe systems in the world, they assume centralized control where it does not exist. The continuing resistance to evolutionary theories is an example: Many people still insist that someone or something must have explicitly designed the orderly structures that we call Life" (Resnick, 1996, p.258). In other words, people incorrectly over-generalize the extent to which events in the world need to be under some kind of volitional control for their occurrence. Thus, a human-in-control or anthropocentric view of the world encompasses not just how activities are managed in day-to-day human lives but comprises every event for which it appears likely a similar process should be in operation.

As McClelland (1984) has pointed out, for most people, there is no compelling reason to believe otherwise. The extent to which individuals see themselves as being able to effect change in themselves and in the world around them suggests that answers of the "need to" form could arise as explanations for any process of change. An example of how this kind of reasoning applies to evolution can be found in how people view infectious diseases and cancer. Because individuals perceive an obvious "need" to be free from such diseases, they believe that merely having such a need will (somehow) lead to every member of a population being free of the diseases, being able to actively avoid them, or being able to avoid debilitating effects once stricken. A more thoughtful examination of these assumptions reveals the problem with this chain of reasoning.

Resnick's notion of the centralized mindset combines two elementary ideas: 1) anthropocentric thought tendencies, and 2) an underestimation of the power of simple, algorithmic processes to produce phenomenally complex outcomes. Dennett (1995) provided an excellent discussion of how the former can lead to an underestimation of the power of the latter. One of Dennett's examples involves the question of whether one should take the bet of a gambler who offers a $100 wager of being able to find a person who, "before your very eyes would proceed to win ten consecutive coin-tosses using a fair coin" (Dennett, 1995, p. 54). Dennett argued that most people are likely to take the "sucker bet" and lose their money because they incorrectly reason that accomplishing such a feat is highly improbable. However, under the right conditions (e.g., having \(2^{10}\) (1024) people in a coin toss tournament), the outcome of producing an individual who has won ten consecutive coin tosses is guaranteed.
The point of using this example is to show that individuals can be notoriously poor judges about the power of algorithmic processes to effect enormously complex and seemingly improbable outcomes in the world. Dennett (1995) chose this relatively simple example because it is, in form, precisely the kind of process that operates to produce the biologically complex adaptations we see in the world. Unfortunately, for many trying to understand evolutionary concepts, personal incredulity (Dawkins, 1995) and a lack of appreciation for and understanding of how this process operates, results in a tendency to take the "sucker bet". That is, people generally reason that apparently improbable events could not possibly occur under "normal" circumstances. Instead, they offer alternative explanations that involve "common sense", "intuitive", experiential, and anthropocentric reasoning for natural phenomena that, upon closer examination, turn out to be incorrect.

The underestimation of the power of algorithmic processes to produce complex outcomes is only one part of Resnick's (1996) observation concerning the tendencies of a "centralized mindset". Demastes et al. (1995a) and Dawkins (1996) provided evidence to indicate just how pervasive the other part of this mindset, anthropocentric thinking, can be. Demastes et al. (1995a) offered the following quote from a subject in their investigation. The answer was provided in response to the researchers' question about the functional reasons for flowers in plants. Notions of McClelland's (1984) idea that evolutionary concepts are never likely to be entertained by individuals until asked to do so can also be observed from the following response: "... I never thought about it [a flower] doing anything for the plant. (...) Honestly, I've always just thought flowers are there because they're pretty. (...) That may sound real stupid, but I've never thought about a flower having a function" (Demastes et al., 1995a, p.654). In other words, according to this subject, flowers are for the enjoyment of humans. Demastes et al. (1995a) labelled this perspective, an aesthetic world view.

Dawkins (1996) has shown that such a perspective goes far beyond naïve personal aesthetics. The following quote indicates the depth and breadth of the type of anthropocentric reasoning that humans can bring to explanations about natural phenomena. Particularly interesting in the following passage is the similarity between Dawkins' young daughter's thoughts on the function of flowers and Demastes et al.'s (1995a) high school subject noted above.
I was driving through the English countryside with my daughter Juliet, then aged six, and she pointed out some flowers by the wayside. I asked her what she thought wildflowers were for. She gave a rather thoughtful answer. 'Two things,' she said. 'To make the world pretty, and to help the bees make honey for us.' I was touched by this and sorry I had to tell her that it wasn't true.

My little girl's answer was not too different from the one that most adults, throughout history, would have given. It has long been widely believed that brute creation is here for our benefit. The first chapter of Genesis is explicit. Man has 'dominion' over all living things, and the animals and plants are there for our delight and our use. As the historian Sir Keith Thomas documents in his Man and the Natural World, this attitude pervaded medieval Christendom and it persists to this day. In the nineteenth century, the Reverend William Kirby thought that the louse was an indispensable incentive to cleanliness. Savage beasts, according to the Elizabethan bishop James Pilkington, fostered human courage and provided useful training for war. Horseflies, for an eighteenth-century writer, were created so 'that men should exercise their wits and industry to guard themselves against them'. Lobsters were furnished with hard shells so that, before eating them, we could benefit from the improving exercise of cracking their claws. Another pious medieval writer thought that weeds were there to benefit us: it is good for our spirit to have to work hard pulling them up.

Animals have been thought privileged to share in our punishment for Adam's sin. Keith Thomas quotes a seventeenth-century bishop on the point: 'Whatsoever change for the worse is come upon them is not their punishment, but a part of ours.' this must, one feels, be a great consolation to them. Henry More, in 1653, believed that cattle and sheep had only been given life in the first place so as to keep their meat fresh 'till we shall have need to eat them' (Dawkins, 1996, pp. 256 - 257).

The point of revealing just how ubiquitous a human-centred view of the world can be in the kinds of explanations individuals offer when discussing natural phenomena is this: if there is any progress to be made in showing how this form of reasoning can obscure deeper understanding of evolutionary processes, then it is necessary to get individuals to be able to adopt a perspective that is distinctly not human (Dawkins, 1996). That is, to overcome the pervasive influence anthropocentric thinking can have in clouding one's understanding of basic evolutionary processes, a certain form of empathy may be needed. Thus, as Dawkins (1996) suggested, this empathy would be equivalent to shifting one's human perspective to that of, for example, the flower's, the bee's, the tree's, the salamander's, the cheetah's, or the ant's perspective. It is reasonable to expect
that this process of shifting perspective away from a human-centred view of the world to the world of the organism in question may help individuals to understand some of the processes and constraints operating at this non-human level.

To date, no reviewed investigations focused on asking subjects to adopt an interspecies perspective (i.e., role-playing at the animal’s level) to assist with conceptual understanding of evolutionary processes. However, a more traditional use of role-playing has been used in the context of learning about the historical aspects of evolutionary theory (Duveen & Solomon, 1994). Duveen and Solomon gave students descriptions of individuals' attitudes and behaviours towards Darwin’s theory of evolution. These investigators argued that in order to be an effective role-player, a student must be active in understanding the views of their character and be able to defend the biological concepts attendant in the role. In their study, a debate ensued among role-playing participants and, as a result, the researchers suggested that many of the issues surrounding the evolution controversy emerged spontaneously.

Duveen and Solomon (1994) indicated that the influence of role-playing on learning may be mediated by the need to empathize with one’s role and with others involved in the debate. Some support for this notion can be found in the social psychological literature dealing with the persuasive effects of role-playing (e.g., Worchel & Cooper, 1983). Role-playing at the level of a non-human organism may confer exactly the same kinds of learning outcomes for the same reasons as the traditional role-playing used by Duveen and Solomon.

Another factor that has received some attention in trying to account for the wide differences observed in students’ understanding of evolutionary concepts is reasoning ability. Lawson and Thompson (1988) used four different predictor variables (reasoning ability, mental capacity, verbal intelligence, and cognitive style) to explore the relationships these variables had with subjects' understanding of evolutionary processes. The investigation was conducted in three phases. First, grade seven students (N=131) were administered scales designed to measure each of the four predictor variables noted above. Second, students were given one month of instruction by their teachers on evolution and genetics via lectures, discussions, readings and other student activities. Finally, each student's knowledge of evolutionary concepts was assessed with the use of open-ended essay questions that dealt with topics involving evolution by natural selection and genetics. Each student’s response to a question was scored for the presence or
absence of a misconception. The total number of misconceptions evident on a student’s test was the dependent measure of interest. Lawson and Thompson found that reasoning ability was the only significant predictor of the number of misconceptions held by a student. As a student’s reasoning ability score increased, the number of misconceptions apparent on the posttest decreased. Overall, reasoning ability accounted for approximately 20% of the variance evident in posttest scores.

Lawson and Thompson (1988) concluded that “formal [operational] reasoning patterns are necessary for the elimination of some biological misconceptions” (p. 743). They suggested that such reasoning ability facilitated student learning by helping them to be aware of the scientific conception, by showing how it was different from their own ideas, and by being able to connect how a scientific model is supported by the evidence in a way that their own ideas were not. Kuhn (1991), in a study that examined the reasoning processes of adults regarding socially complex problems (i.e., why prisoners return to crime after being released from jail, what causes children to fail in school, what causes unemployment), came to an almost identical conclusion. Kuhn found that only 26 of the 160 subjects interviewed were able to think about a theory in a consistent manner when evaluating their personal responses to the three problems she posed.

To accomplish this second-order or metacognitive thinking about a theory, an individual must have a mental representation of the theory that can then be acted on and evaluated, relative to mental representations of evidence that are differentiated from the theory -- permitting the construction of relations between the two -- and relative to mental representations of alternative theories to which it can be compared. As a description of “the way the world is,” a theory offers little value. It assumes power only to the extent that one can envision alternatives with which it competes, as well as evidence against which it can be evaluated (Kuhn, 1991, p. 267-268).

The research by Lawson and Thompson (1988) and Kuhn (1991) supports a large body of literature on students’ reasoning in science (Griggs & Cox, 1983; Kuhn & Ho, 1977; Mynatt, Doherty & Tweney, 1977; Tweney, Doherty, Worner, Pliske & Mynatt, 1980; Wolpert, 1993). Generally, these studies suggest that the logical examination of evidence, as it relates to the use of theories, is a very challenging cognitive task that is performed poorly by most students.
In a follow-up investigation to Lawson and Thompson (1988), Lawson and Weser (1990) studied 954 college students enrolled in an introductory biology course. Lawson and Weser argued that reflective subjects (i.e., individuals who scored high on a test of logical reasoning) would be more likely to reject commonly held nonscientific beliefs as compared to intuitive subjects (i.e., individuals who scored low on a test of logical reasoning). Lawson and Weser were very specific in identifying the types of nonscientific beliefs subjects held (see Table 2).

Overall, the results of Lawson and Weser's (1990) study were mixed. As predicted, reflective subjects were more likely to move away from beliefs of orthogenesis, nonreductionism, vitalism, and teleology and move towards the accepted scientific conceptions compared to intuitive subjects. However, reflective subjects were no more likely than intuitive subjects to move away from beliefs related to creationism, the soul, and nonemergentism and move towards scientific conceptions. Overall, this study and Lawson and Thompson's (1988) study appear to indicate that reasoning ability accounts for only some of the variance observed in why students hold misconceptions about evolutionary concepts.

Table 2.
Nonscientific beliefs examined in 954 nonmajor biology students (adapted from Lawson and Weser, 1990).

<table>
<thead>
<tr>
<th>Nonscientific belief</th>
<th>Description of belief</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special creation</td>
<td>The belief that living things were created by an act of God.</td>
</tr>
<tr>
<td>Orthogenesis</td>
<td>The belief that evolution is directed towards perfection by an inherent force of living things.</td>
</tr>
<tr>
<td>The soul</td>
<td>The belief that living things differ from nonliving things because they possess a spirit distinct from the physical.</td>
</tr>
<tr>
<td>Constitutive nonreductionism</td>
<td>The belief that living and nonliving things are not composed of similar materials and/or the materials are not subject to the same physical laws.</td>
</tr>
<tr>
<td>Vitalism</td>
<td>The belief that a mystic, nonmeasurable motive force exists in living things.</td>
</tr>
<tr>
<td>Teleology</td>
<td>The belief that events in nature are predetermined by divine guidance for a purpose.</td>
</tr>
<tr>
<td>Nonemergentism</td>
<td>The belief that the whole organism is no greater than the sum of its parts.</td>
</tr>
</tbody>
</table>

Smith and Siegel (1993) were critical of Lawson and Weser's (1990) claim that the beliefs listed in Table 2 represent nonscientific beliefs. They argued that beliefs concerning special creation, the soul, and teleology were examples of personal
convictions that are not open to scientific scrutiny. The researchers suggested that one of the defining characteristics of a scientific hypothesis was the Popperian test of falsification. As such, "the existence of immeasurable forces cannot be subjected to empirical test; by definition (or at least by convention), the existence of God is similarly not testable by data obtained from the five senses. Such beliefs are based on faith, which is 'the evidence of things not seen' (Hebrews 11:1)" (Smith & Siegel, 1993, p. 600). In a footnote to this quotation, Smith and Siegel added that although a particular phenomenon in science is not empirically verifiable, this does not preclude a rational discussion of the concept. Specifically, an exploration of why individuals hold the personal convictions they do is open to scientific investigation (Kurtz, 1999).

The Lawson and Weser / Smith and Siegel debate is one that deals with the role that empiricism and subjective beliefs play in knowledge acquisition and with the nature of science itself. As discussed next, understanding the nature of the scientific enterprise is a critically important aspect of understanding evolutionary concepts.

Scharmann and Harris (1992) conducted an investigation with 19 (12 males, 7 females) practicing secondary science teachers which explored their views on the nature of science and their acceptance of, and anxiety with, evolution. The study was conducted in two phases over a three week period. The first phase (weeks 1 and 2) was used by the researchers to provide subjects with explicit activities that promoted the use of student-centered, small-group discussion. Additionally, subjects were provided with readings and engaged in discussions "to promote a more adequate understanding of the nature of science and why it is that scientists contend the theory of evolution is such a major unifying theme for study in the biological sciences" (Scharmann & Harris, 1992, p. 379). During the second phase of the study (week 3), subjects were asked to develop an activity designed for teaching an evolutionary concept to their students. Also, subjects completed two scales, one on the first day of phase one (pretest) and the other on the last day of phase two (posttest). The first was a Likert-type scale that assessed their philosophical and applied perspectives on the nature of science. The second survey was designed to measure their anxiety about teaching evolution.

Scharmann and Harris (1992) found that the posttest assessment regarding subjects' knowledge of evolutionary concepts showed a significant increase in acceptance and understanding of evolutionary principles compared to the pretest. However, with regard to subjects' philosophical understanding of the nature of science, the researchers
failed to find any significant changes in their pretest and posttest scores. Yet, subjects' posttest measures of anxiety regarding the teaching of evolution were significantly lower when compared to their pretest anxiety levels. It is important to point out that this study appears to indicate that improved knowledge of evolutionary concepts and reduced anxiety about teaching it can be independent of one's philosophical position regarding the nature of science. This is not to say that science instruction, in general, and teaching evolution specifically, do not require or do not benefit from an understanding of how science operates to produce knowledge. On the contrary, it is critically necessary (Hodson, 1988; National Academy of Sciences, 1998; Nickels et al., 1996; Scharmann, 1993; Smith et al., 1995). Regardless of one's specific philosophical position on the nature of science in general, it is sufficient to understand that the practice of science differs significantly from other ways individuals can learn about the world (Cobern, 1994).

Cobern (1994) reported that only 9% of all Americans believe the contemporary Darwinian account of evolution. He argued that unless students' beliefs and disbeliefs are addressed, they are unlikely to attain the kind of conceptual change that is required for a scientific understanding of evolutionary ideas. Thus, for Cobern, the starting point of lessons on evolution should be a classroom dialogue that encourages students to discuss their beliefs about the subject. Student beliefs are thus central in teaching evolutionary concepts because,

The question of what counts as believable is important in science education precisely because teaching takes place across groups, e.g., scientist to non-scientist. As noted earlier, a key point in constructivist thought is that meaning is an interpretation based on prior learning. Prior learning includes various scientific concepts, but it also includes culturally dependent presuppositions or assumptions about what the world is ultimately like and what constitutes first causes. This is a definition for a worldview, and the claim of cultural constructivism is that learning is influenced by worldview (Cobern, 1994, p. 587).

Recall, however, that for most individuals, there will have been very little opportunity for any prior learning of evolutionary concepts. As a consequence, most of the reasoning that will be applied to understanding evolutionary phenomena will be consistently intuitive and nebulous both in form and in depth.
In contrast to Cobern (1994), Smith (1994) suggested that using beliefs as the focus of teaching evolution is likely to confuse, not benefit students. Smith argued that the term “belief” is too often interpreted by students to be equivalent to personal opinion. However, the tacit meaning of belief, when it is used by scientists, implies an idea that is supported by the available evidence. For Smith, acknowledging students’ worldviews could help a science teacher because it increases the likelihood that students will at least listen to what the teacher has to say. However, Smith fears that using worldviews as the central focus of discussions will leave students with the idea that, in science, they are free to construct subjective and unsubstantiated explanations as they wish. Instead, promoting the careful use and understanding of terms like “accept” and “belief” will help students appreciate the distinction between how they may be using the term and how, by comparison, when used in a scientific context, the terms have unique and narrow definitions. Thus, when a scientist uses the term “accept”, it connotes that the rules of empirical evidence are operating and, as such, personal convictions, opinions, and beliefs are not the criteria for judging the veracity of a truth claim (Smith, 1994). Smith concluded that,

...the distinction between believing and accepting may be a subtle one for many, it is crucial to understanding the nature of science; moreover, drawing carefully the distinction between belief (or faith) in the absence of objective evidence and acceptance that is based on evidence provides an excellent opportunity for helping students understand what science is. In my view, in fact, the primary reason for including evolution in the curriculum, other than the obvious value of a meaningful understanding as a basis for understanding the rest of biology, is that it provides the wonderful opportunity for addressing pervasive misconceptions about the nature of science (p. 595).

Smith's (1994) and Cobern's (1994) perspectives reveal the critically important role of language for how students come to understand evolutionary concepts. Terms and phrases, especially in this domain, have a habit of taking on a life and meaning of their own (e.g., Dawkins, 1982, see chapter 10). Consequently, there is often a disparity between what scientists mean by a given term and the evidence that supports its use and what students understand about the same term. The following is a short list of some of the terms and phrases that tend to create confusion among students; accept, adapt, adaptation, belief, chance, cause and effect, evidence, evolution, explanation, fact,
fitness, gene, mutation, need, random, selection, survival of the fittest, theory, time, and variation (Bishop & Anderson, 1990; Buss, Haselton, Shackelford, Bleske, & Wakefield, 1998; Dawkins, 1982; Jensen & Finley, 1996; National Academy of Sciences, 1998; Smith et al., 1995). Thus, with regard to learning evolutionary concepts, language interpretation and word definition appear to be partly responsible for the classic problem that educators have always faced when trying to teach scientific concepts; a difference among what is intended (by scientists), what is delivered (by educators) and what is received/learned (by students).

Another point that is important to consider when seeking explanations for why students have difficulty understanding evolutionary concepts is the relationship most scientific constructs, models and theories have with mathematics. Evolutionary theory is (and was when Darwin postulated it) fundamentally mathematical. As Wilson and Bossert (1971) noted:

The material [in this book] is elementary, and it is also fundamental to the understanding of a large part of evolutionary biology. The methods stressed are mathematical model building, measurement techniques, and problem solving, because as teachers we believe that the beginning student of biology, as well as advanced researchers, must heed Lord Kelvin's warning that "Unless you have measured it, you don't know what you are talking about." Although to apply the dictum in a blanket fashion would be unwarranted and excessive, we have noticed that much of the confusion and misunderstanding in the contemporary literature of evolutionary theory and ecology, fields that have received more than their share of polemics, arise when the disputants can't measure it (p. 9).

Wilson and Bossert (1971) are advocating that in order for students to understand evolutionary biology, they need to use and to understand the mathematical methods and models that are an inherent aspect of learning the concepts. Moreover, they noted that many of the mathematical skills needed to understand most evolutionary concepts do not exceed those learned in high school (e.g., calculating proportion, simple algebra, basic probability theory).

If basic mathematical skills are needed to understand evolutionary theory, then is it the case that many of the difficulties students have in learning the concepts stem from a lack of proficiency with numbers? Pinker (1997) has this to say about the average student's mathematics ability.
American children are among the worst performers in the industrialized world on tests of mathematical achievement. They are not born dunces; the problem is that the educational establishment is ignorant of evolution...

Mastery of mathematics is deeply satisfying, but it is a reward for hard work that is not itself always pleasurable. Without the esteem for hard-won mathematical skills that is common in other cultures, the mastery is unlikely to blossom. … Without an understanding of what the mind was designed to do in the environment in which we evolved, the unnatural activity called formal education is unlikely to succeed (pp. 341-342).

We appear to have a chicken-and-egg dilemma. Wilson and Bossert (1971) suggested that we have difficulty understanding evolution concepts because we do not have a grasp of basic mathematics. According to Pinker (1997), we are poor at mathematics because we do not understand evolution and how it has shaped the brains we have (see also Barkow, Cosmides & Tooby, 1992; Buss, 1995; Cosmides & Tooby, 1992; Cosmides & Tooby, 1994; Cosmides & Tooby, 1996, for a cogent discussion of this topic).

Paulos (1988) suggested a notion similar to that of Pinker (1997). Our primitive ancestors evolved in relatively simple environments. In such environments there were likely to have been strong selection pressures operating such that a brain capable of establishing the genuine connections and patterns relevant to survival in that world would have proved a very successful adaptation. For example, those individuals with brains capable of making important survival inferences (e.g., That red berry came from plant 'A' and didn't make me sick. That red berry came from plant 'B' and made me ill. Therefore, only eat red berries from plant 'A'.), would have had a distinct advantage over those who could not make such connections. Examples of this kind may seem trivial but a relatively small, yet desperately critical, set of such contingencies would have confronted our progenitors. To the extent that being able to make such distinctions was heritable, those individuals with the cognitive capacity to sort out which connections were important from those that were not would have been more likely to survive and produce offspring.

However, as Paulos (1988) noted, this primitive tendency, which had operated to give our species the niche advantage it now enjoys, makes it even more important than ever to have strong numeracy skills.
Our innate desire for meaning and pattern can lead us astray if we don’t remind ourselves of the ubiquity of coincidence, an ubiquity which is the consequence of our tendency to filter out the banal and impersonal, of our increasingly convoluted world, and, as some of the earlier examples showed, of the unexpected frequency of many kinds of coincidence. Belief in the necessary or even probable significance of coincidences is a psychological remnant of our simpler past. It constitutes a kind of psychological illusion to which innumerate people are particularly prone (p. 112).

Is it possible that the kinds of specious connections that Lamarck and the majority of students today so often make in their explanations of evolutionary events are remnants of ancient but highly useful, cognitive inference processes that continue to operate in the context of modern environments? Are the scientific enterprise, in general, and mathematics, specifically, the tools we now use to help us unmask our primeval cognitive and emotional selves? There is a rapidly growing body of research that suggests both of these questions can be answered with an unequivocal, “yes” (Barkow et al., 1992; Buss, 1995; Cosmides & Tooby, 1996; Paulos, 1988; Pinker, 1997; Wolpert, 1993).

Most of issues and factors discussed above were related to variables concerning knowledge in general. The following discussion relates to variables of a psychological nature. Klaczynski and Narasimham (1998) suggested a possible reason to explain the kinds of cognitive biases evident in explanations of scientific phenomena. Their study, in part, examined the extent to which a defence of one’s beliefs was motivated by a need to protect one’s ego (i.e., self-views, self-esteem, and affective desires). Forty-two fifth-grade, 42 eighth-grade, and 41 eleventh-grade students worked in small, age-similar groups to try and solve nine hypothetical problems that dealt with cause and effect relationships among variables such as religious beliefs, parenting behaviour, morality, sexual harassment, and creativity. In the problems, a hypothetical researcher proposed a causal justification among the variables to explain the problem. In addition, subjects completed an ego-investment questionnaire which assessed, on a 9-point scale, the extent to which subjects expressed emotional attachment to their religions. Subjects were also given scientific reasoning scores based on two indices. The first index asked subjects to rate (on a 9-point scale) the perceived strength of the researcher’s conclusions in the hypothetical problems. The second index used subjects’ written justifications for the rating given in the first index.
The results suggested that ego-defence accounted for some of the variance in the reasoning biases used by students in explaining perceived causal events. Klaczynski and Narasimham (1998) concluded that cognitive reasoning biases (like those noted above, and also in Kuhn & Ho, 1977; Mynatt, et al., 1977) and biases related to the motivation to protect one's ego were operating. The authors suggested that both these biases must be explored in order to get a complete picture of students' reasoning as it is applied to causal explanations. Thus, it appears that Klaczynski and Narasimham's (1998) findings support the idea that it is necessary to examine the type and strength of beliefs individuals bring to their understanding of scientific phenomena. As these researchers found, such beliefs can be the source of strong motivational forces that produce barriers to understanding important causal reasoning processes inherent in many scientific problems.

**Perspectives on the Nature of Science**

There has been a gradual shift in the philosophy of science away from the traditional view that science is an enterprise free of human bias conducted with a specific methodology where its knowledge and products reflect universal truths (Hempel, 1966; Pera, 1994; Rudner, 1953). For example, Pera (1994) presented arguments for rejecting what he terms the "Cartesian Syndrome". This syndrome is characterized by three themes: 1) "There is a universal and precise method that demarcates science from any other intellectual discipline" (Pera, 1994, p. 4), 2) "The rigorous application of this method guarantees the achievement of the aim of science" (Pera, 1994, p. 4), and 3) "If science possessed no method, it would not be a cognitive and rational endeavor" (Pera, 1994, p. 4). In place of these theses, Pera argued for a model of science that is based less on method and more on "scientific argumentation": an attempt to persuade the listener that the propositions forwarded are veridical.

Thus, contemporary philosophers of science have begun to adopt the perspective that science's processes and products, like all human endeavors, are to some extent shaped by the social context in which the ideas exist. Moreover, one of the most important factors in this social milieu is the view held by others. Part of this social process requires learners to interact with their peers, preferably in small groups (e.g., dyads or triads) in a collaborative effort to solve the problem at hand. With respect to learning in the domain of science, this investigation placed a strong emphasis on this philosophy of social exchange within small groups. This model of science, which posits
that knowledge building is an enterprise influenced by social and contextual factors, is gradually replacing the traditional Cartesian model noted above.

However, is one's perspectives or philosophy regarding the nature of science influential in shaping students' understanding of evolution? Nickels, et al. (1996) suggested that it is and proposed four major themes as critical for teaching evolutionary biology successfully. First, students and teachers must understand that science is inherently uncertain yet capable of producing very reliable results. Second, science is learned best when it is presented in a non-dogmatic fashion. Third, the theory of evolution by natural selection is a quintessential example of scientific thinking, methods, processes and knowledge. Fourth, human evolution is an excellent case study for evolutionary theory. Of these four themes, Nickels et al. (1996) indicated that it was the first one, understanding the nature of science, that was critical to understanding evolutionary ideas. In other words, students (and teachers) must understand that of the many ways of knowledge acquisition that exist in the world, how they view the enterprise of science will fundamentally influence the way in which they interpret the evidence that is offered in support of evolutionary concepts. An important aspect of this investigation is to explore the extent to which participants' perspectives on the nature of science are related to their understanding of evolutionary concepts.

Intentions to Teach Evolution by Natural Selection

It was suggested earlier that pre-service science teachers are an important group to investigate because of their future role in the education of students. In teaching, there can be important differences among an intended curriculum (e.g., the curriculum as it appears in Ministry guidelines), the curriculum as it is delivered by the teacher, and the curriculum as it is interpreted and learned by students. It is reasonable to assume that if a motivated teacher has the requisite knowledge and a belief that such knowledge could be of value to students, then he or she should endeavour to put forth their best pedagogical effort to teach it. Because of the potential for a lack of knowledge about evolutionary concepts and a conflict between the tenets of evolutionary theory and a teacher's belief system, there may be a large disparity between the evolutionary curriculum as it is intended to be implemented and how that curriculum may actually be delivered by some teachers. Thus, identifying some of the reasons why a teacher will or will not teach a subject, especially if teaching that subject creates a conflict in one's personal beliefs and
values (or both), would be of obvious use to the teacher, the students, and the school. Is there a way to predict whether a teacher's knowledge, beliefs and values about evolution could affect that individual's propensity to teach the theory of evolution by natural selection?

One aim of this study was to explore the degree to which participants' knowledge and beliefs about the theory of evolution by natural selection can affect their intentions to teach the theory in their own classrooms. The theoretical model that was used to examine this aspect of teacher behaviour is the Theory of Planned Behavior (Ajzen, 1985).

This theory is unique in that Ajzen claims, by using a minimal set of assumptions and a small number of predictor variables, some types of human behaviour can be predicted with a fair degree of reliability. His Theory of Planned Behavior proposes that actual behaviour (e.g., teaching a science lesson on evolution) is highly related to one's intention to perform the action. The strength of the intention is inferred from three main factors. Figure 1 shows all of the major relationships in the model.

**Figure 1.**

First, part of the variance in a person's intention to do something resides in an individual's attitude towards that action. Second, the amount of social pressure the person feels to perform or not to perform the behaviour (subjective norm) accounts for an additional proportion of the variance in a person's intention to act. The third significant
amount of variance that accounts for a person’s intention to perform a given action is the degree to which an individual feels that he/she has control over performing the behaviour.

The three major elements of the model are combined in the following ways. First, a person’s attitude (A) about a given behaviour is a function of the beliefs (b) that a person has about certain consequences regarding the behaviour and an evaluation (e) of those consequences (Petty & Cacioppo, 1981). Beliefs relate to how likely it is that performing a given act (e.g., teaching evolutionary concepts) will lead to specific consequences (e.g., upsetting students). Evaluations refer to the subjective assessment of how good or bad a particular consequence may be. Second, a subjective norm (SN) is a function of one’s normative beliefs (nb) and one’s motivation to comply (mc). Normative beliefs are related to an individual’s expectations that personally important individuals or groups would endorse the given behaviour. Motivation to comply relates the individual’s willingness to do what personally important individuals and groups would like. Third, perceived behavioural control (PBC) is a function of a person’s beliefs about the factors that control his or her ability to engage in the behaviour (cb) and the likelihood that a person could actually control those factors (lo). All of these factors are related in the following mathematical relationship:

\[
I = W_1 \left[ \sum_{i=1}^{N} b_i * e_i \right] + W_2 \left[ \sum_{i=1}^{M} n b_i * m_a \right] + W_3 \left[ \sum_{i=1}^{P} c b_i * l \alpha \right]
\]

Five of the six sub-scales (i.e., b, nb, mc, cb, lo) are composed of items that are anchored at -3 by “extremely unlikely” and at +3 by “extremely likely” (e.g., see Appendix C). Participants use a 7-point Likert scale to rate the likelihood that the event described by an item would occur. The other sub-scale, (e), is composed of items that are anchored at -3 by such terms as “extremely bad”, “extremely useless”, “extremely harmful” and at +3 by such terms as “extremely good”, “extremely useful”, “extremely beneficial”. Participants use this 7-point Likert scale to rate their evaluation of the consequences of that event if it were to occur. For example, a participant might believe (b) that it was “slightly likely” (b = +1) that teaching evolution by natural selection “could offend some students”. Also, this participant might evaluate (e) this outcome as “slightly bad” (e = -1). According to Ajzen (1985), this individual’s attitude (b x e) towards teaching evolution by natural selection for this item is slightly negative (-1).
Overall, a participant's score could range from -9 to +9 for any one item that comprises the three major sub-scales. The individual item scores are then summed for each of the major sub-scales, attitude (A), subjective norm (SN), and perceived behavioural control (PBC), according to the formula noted above. To compare the relative influence of each sub-scale, a mean score for each of A, SN, PBC is obtained by dividing the total sub-scale score by the number of questions that comprise the sub-scale. In this investigation, the 'A' sub-scale was composed of 42 (2 x 21) items, the SN sub-scale was composed of 14 (2 x 7) items, and the PBC scale was composed of 14 (2 x 7) items.

Generally, a positive attitude score suggests that a participant has a favourable attitude towards that item, and a negative scores indicates a negative attitude. A positive subjective norm score suggests that a participant has a belief that important reference groups (e.g., other teachers, religious groups) endorse the behaviour and that she/he is willing to comply with a particular referent group. A negative subjective norm score suggests that a participant has a belief that important reference groups may not endorse the behaviour and that she/he is willing to comply with that referent group. A positive perceived behavioural control score suggests that a participant has a belief that performing the behaviour is within that persons capacity to do and that it will be relatively easy to perform. A negative perceived behavioural control score indicates that a participant has a belief that performing the behaviour may be beyond one's ability to do so and that it will be relatively difficult to perform.

The result, when all the elements of the equation are combined, is an intention (I) score. The higher the intention score, the more likely it is that a person will engage in the given behaviour. Different weights can be applied to each factor depending on the number of questions used in each of the sub-scales or on contextual variables that might influence the relative importance of each element. Theoretically, ITEQ scores can range from a minimum of -27 to a maximum of +27 (the sum of the mean values for A, SN, and PBC).

In a science related application of this theory, Crawley and Koballa (1994) tried to predict enrollment in a grade 11 Chemistry course. First, the authors collected responses from students in six grade 10 classes concerning their beliefs about the advantages and disadvantages of taking Chemistry. Then, the responses were reviewed and a 50-item questionnaire to assess a student's intention to take grade 11 Chemistry was developed.
using the Theory of Planned Behaviour as the model for item construction. Next, in the experimental condition, the researchers attempted to change students' attitudes towards taking Chemistry by exposing them to stories which contained messages that supported the favourable beliefs and discredited the unfavourable beliefs collected from students in the first part of the experiment. The control group did not receive these messages. Last, the 50-item questionnaire developed to assess behavioural intentions towards taking Grade 11 Chemistry was given to students. The results showed that students in the attitude manipulation condition were significantly more likely to enroll in Chemistry than were students in the control condition. Moreover, when the intention subcomponents of the 50-item questionnaire were examined, students in the experimental condition showed more positive changes in all of the cognitive subcomponents of the theory.

In summary, an examination of pre-service science teachers' intentions to teach evolutionary concepts is an exploratory adjunct to the main purpose of this thesis. In educational practice, it is necessary that teachers feel comfortable with the material they teach. The Theory of Planned Behaviour could help to illuminate more precisely why a teacher may or may not have a strong intention to teach evolutionary theory. For example, it may be that the teacher believes (b) he or she lacks the necessary knowledge or, it may be that the teacher feels that teaching evolutionary theory would conflict with the religious group to which he or she is strongly committed (mc). In any case, the model explores a broad range of potential factors that could affect how or whether a teacher implements a science curriculum in a manner consistent with the ethos of domain specific teaching. The items developed for implementation of Ajzen's (1985) model for the purposes of this study can be found in Appendix C.

Summary

It appears that a significant majority of students have difficulty in understanding evolutionary concepts. Several explanations have been offered to account for the problems students face when trying to understand evolutionary concepts. These accounts include a "centralized" mindset, anthropocentric thinking, difficulties with formal reasoning, motivation to defend one's ego, abstruse scientific terminology and a lack of appropriate mathematical skills.

Table 3 is a summary of these factors and includes a brief comment on the relevance or importance of each for understanding evolutionary concepts. The variables
listed in Table 3 are by no means exhaustive. There will no doubt be other idiosyncratic factors operating at the level of the individual learner. The literature reviewed in this chapter, however, suggests that the factors noted in Table 3 will encompass a large majority of the conceptual and epistemological challenges that students face when trying to understand basic evolutionary concepts.

Table 3.
**Important factors related to conceptual difficulties in understanding evolutionary concepts.**

<table>
<thead>
<tr>
<th>Factor</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underestimation of the ubiquity and power of algorithmic processing</td>
<td>This factor may be related to a general level of innumeracy and mathematical ability.</td>
</tr>
<tr>
<td>Anthropocentric thinking</td>
<td>A very common mental tendency that may obscure natural phenomena that are outside normal human experiences.</td>
</tr>
<tr>
<td>Nebulous or non-existent preconceptions</td>
<td>Without any well connected evidential foundation for reasoning about evolutionary processes, individuals tend to rely on intuitive, common sense, or experiential reasoning to support their explanations.</td>
</tr>
<tr>
<td>Absence of prior learning</td>
<td>Improving the biology curriculum demands using evolutionary concepts as the foundational theoretical framework. This perspective is, to some extent, constrained by a &quot;chilly&quot; legal and political context which continues to operate in most North American classrooms.</td>
</tr>
<tr>
<td>World view</td>
<td>It may be important to acknowledge students' non-scientific beliefs.</td>
</tr>
<tr>
<td>Reasoning ability</td>
<td>Formal operational thought processes may be an important prerequisite for understanding evolutionary concepts.</td>
</tr>
<tr>
<td>Nature of science</td>
<td>An understanding of how the practice of science operates to produce knowledge and how this process is different from other &quot;ways of knowing&quot; will be important.</td>
</tr>
<tr>
<td>Use of language/terms</td>
<td>It is important for students to be able to distinguish between how certain terms are used in the vernacular and how those same terms are used by Biologists and scientists.</td>
</tr>
<tr>
<td>Psychological variables a) Ego defence b) Primitive &quot;inference engines&quot;</td>
<td>Ego defence points to the importance of acknowledging students' beliefs in learning science concepts. Understanding evolutionary concepts may be difficult because our brains are operating outside the primitive environments in which these brains originally evolved.</td>
</tr>
</tbody>
</table>

Additionally, the conceptual difficulties students have in understanding evolutionary concepts seem to be very resistant to traditional compensatory efforts. That is, these problems persist even after curriculum interventions have been designed to address them. At least part of this issue is related to the fact that evolutionary events are virtually impossible to demonstrate experimentally given the constraints of time and equipment typical of most learning environments. As discussed in the next chapter, one possibility for circumventing these particular difficulties is to use computer simulations of evolutionary processes.
Another aspect of learning evolutionary concepts is related to views on the nature of science. Contemporary philosophy of science suggests that learning science concepts requires an understanding of how knowledge is constructed in a social context. As such, sharing one's views on science problems within small groups is expected to illuminate learners' ideas in a way that working on the same problem alone would not. Also, an individual's personal views on the nature of science itself was discussed as a factor relevant to how a student will view the theory of evolution.

Last, unless pre-service science teachers' knowledge of evolutionary concepts translates into actual teaching behaviour, students' misconceptions in this domain can be expected to persist. A brief discussion of the Theory of Planned Behaviour (Ajzen, 1985) explored how the theory could be used as a means of examining participants' intentions to teach evolutionary concepts.
Chapter 2

The Computer: A Tool for Learning

Nineteen fifty-three, the year of the double helix, will come to be seen not only as the end of mystical and obscurantist views of life; Darwinians will see it as the year their subject went digital (Dawkins, 1995, p. 20).

Computers in Education: An Overview

The use of computers in educational settings is a relatively new phenomenon in Ontario (McLean, 1992). For example, Mingail (1997) reported that in less than 15 years, the presence of computers in K-12 schools has gone from almost zero in 1980 to a ratio of about one computer for every 10 students. This number is more than double the ratio it was just seven years ago. However, as with most statistics, this proportion obscures some important details. For example, Mingail noted that the ratio of multimedia computers to students, machines that offer students a much richer tool for learning, stands at only 1 to 35. Additionally, more than half of all school computers still reside in "labs". In most schools, computer labs, while helping to provide equal opportunity for use of a limited resource, also restrict the kind of access that is needed to integrate computers into the curriculum. Furthermore, less than half of the teachers in the K-12 system have any formal computer training (Mingail, 1997). Nonetheless, these statistics do not reveal how schools with relatively few multimedia computers, students with less than adequate access to computers, and teachers who are unprepared to integrate computers with current curriculum will affect the degree to which students can learn with the aid of computers (Fisher, 1999).

As Cromer (1997) pointed out, there are few compelling reasons that justify a multi-million dollar investment in computer equipment for classroom use when there is scant evidence that time spent using computers to learn is any more productive than an equivalent amount of time spent on more traditional learning activities. In Cromer's view, "Research in educational technology often looks like a solution in search of a problem. It's easy to fall in love with high-tech gizmos -- I've done it myself -- and to lose sight of the ultimate objective: the education of students" (Cromer, 1997, p. 127).

There are many other critics who are skeptical of claims that using computers as an educational tool will improve learning (Fisher, 1999). On the other hand, if one is interested in learning how to use a computer and its software, then there is no choice. In
fact, Becker (1993) reported that more than 50% of the time spent on computers in classrooms was used in the service of learning about computers and application software.

How is the other 50% of the time used? According to Becker (1993), who reported statistics gathered from a 1989 national US survey, only English teachers appeared to use computers in a way primarily related to their subject. For example, English teachers who reported using computers on more than five occasions in a year, indicated that 45% of that time was spent using word processing programs. Drill and practice exercises were the second most frequent uses of computer time (32%) reported by English teachers. In contrast, math teachers who used computers more than five times a year reported using graphing and spreadsheet programs no more than 3% of the time. The primary use of computer time reported by math teachers was drill and practice (25%). Science teachers reported using science simulations about 12% of the time. Similar to math teachers’ use, drill and practice occupied the highest use of computer time for science teachers at 26%.

In general, what these usage statistics suggest is that computers tend to be under-utilized as an integrated learning tool in subject-specific domains. In other words, there may be specific writing challenges, unique math questions, or abstract science concepts that could be rendered easier to understand by implementing a computer-mediated approach to teaching in these domains. This claim rests on the assumption that computers can provide a way to teach and a way to learn that is not just equivalent, but is superior to, traditional classroom practices. The next section will review some of the literature on how computer simulations are becoming an increasingly important cognitive tool for learning science concepts.

Computers in the Classroom: Epistemological Perspectives

Derry and Lajoie (1993) used three broad categories to describe the theoretical perspectives for how computers are used as tools in an educational setting: 1) model builders, 2) non-modellers, and 3) a group that bridges the gap. Model builders or “modellers” believe that computers are effective tools when they are used as tutoring systems. Such systems are described in the literature by names such as teaching machines, computer based instruction (CBI), computer based tutoring (CBT), computer assisted instruction (CAI), and computer based learning (CBL). Modellers assume that the learning accomplished by students is primarily rule driven, can be represented
symbolically, can be anticipated, and benefits from structure, direction and immediate feedback as the learner interacts with the "intelligent tutoring system" (ITS). An ITS relies on implementing, within the computer, the best procedures for learning a particular problem or concept. Typically, the best procedures for learning are based on the knowledge and actions used by experts to understand those concepts. Next, the error prone ways in which novice learners try to solve the same problems are "diagnosed" by the ITS. This information is used in conjunction with expert paths to the solution to help guide the learner to a better understanding of the concepts being studied.

In contrast, non-modellers view computers as tools for collecting, analyzing, and presenting information. This perspective is based on the assumption that specific cognitive models will be inadequate and too rigid for transmitting what needs to be learned, especially for complex problems (e.g., social problems and abstract concepts). Non-modellers posit that it is the learner, not the computer, who must take control over instructional decision making. Non-modellers are likely to be neo-Piagetians who favour learning theory models like cognitive apprenticeship, situated cognition, and constructivist learning (Derry & Lajoie, 1993).

Derry and Lajoie (1993) described the third group, those who fall between the two ends of the modeller/non-modeller continuum, as believing that "computers can and should serve part of the cognitive mentorship function without giving over total control of the learning and assessment process to system users (teachers and students)" (p. 7). In this view, computers are tools that can provide students with new ways of viewing a particular problem within a structured, procedural framework while simultaneously supporting the idiosyncratic ways in which individuals and communities of learners problem solve (Scardamalia, Bereiter, McLean, Swallow, & Woodruff, 1989).

Theoretically, Derry and Lajoie suggest that this middle camp represents an educationally sound balance between the need for modelled learning and learning that can occur in contextually unique social settings.

What are some of the characteristics of a computer tool that incorporates the best of an effective ITS while concomitantly utilizing the learner as the active agent responsible for her/his own knowledge building? Reusser (1993) identifies eight primary principles and several sub-principles that define the design elements of such a tool (see Table 4).
### Design Principles or Characteristics

| 1. | Design and use computer-based tools pedagogically, that is, as cognitive instructional tools for mindful teachers and learners in a culture of problem solving. |
| 2. | Extend and empower the minds of intentional learners. |
| 3. | Provide learners with some guidance according to the "principle of minimal help". |
| 4. | Have students construct and externalize their mental models. |
| 5. | Provide students with intelligible and effective representational tools of thought and of communication. |
| 5a. | Useful representational systems or formats allow students, while creating and elaborating a mental representation of a problem, to capture the essential structural features of the problem and to differentiate the problem from classes of similar problems. |
| 5b. | Representational notations guide students' problem-solving and knowledge-construction activities by supplying operative, iconic, and symbolic forms of solutions and — more generally — of understanding. |
| 5c. | Good representational formats enforce intentional structural editing, that is, they encourage students to view their manipulations of a representation as semantically meaningful operations. |
| 5d. | Effective representations allow rapid recognition and retrieval of relevant information, mainly by reducing abstract problem-solving and reasoning processes in favour of processes which come closer to perceptual operations, to seeing things. |
| 5e. | Effective representational systems provide a structural basis (platform) upon which, using domain-specific or general problem-solving methods or strategies, the user can act, manipulate, and reason. |
| 5f. | Instructionally valuable representations serve to mediate between idiosyncratic and informal analyses of problems and concepts and shared cultural and more formal analyses. |
| 5g. | Hence, cognitively plausible instructional representations should be parts of learning systems in which multiple representations, designed to preserve different aspects of an invariant relational structure, are linked in a yoked fashion. |
| 5h. | Externalized representations supply teachers and students with a conceptual language to communicate and talk about what is to be learned. |
| 6. | Promote the use of comprehension-related strategies. Together with representational formats, general and domain-specific strategies are the cognitive tools of thinking and problem solving. |
| 7. | Encourage reflective and self-directed learning. |
| 8. | Extend the use of computer-based instructional tools into a supportive classroom culture of collaborative learning. |

Some of Reusser's eight principles put him squarely in the non-modeller's camp (e.g., principles 1, 7, and 8) whereas other principles (e.g., principles 2, 3, and 4) align him with generally accepted, albeit somewhat vague, ideologies of pedagogy and learning. Derry and Lajoie (1993) categorized Reusser (1993) as a "non-modeller" with respect to his theoretical views on computers as cognitive tools. However, principles five and six appear to have the distinct flavour of a modeller's philosophy. Generally, the
information presented in Table 4 seems to indicate that if one is going to employ the use of computers as an educational tool, rigid allegiance to either end of the modeller/non-modeller continuum is likely to result in missed opportunities for learners.

Thus, Reusser's eight principles suggest that there is a need for the computer to provide some structure for the problem to be solved and procedural guidance (principles 5 and 6) while simultaneously allowing learners to be active participants who are responsible for their own learning in social contexts (principles 1, 2, 3, 4, 7 and 8). In other words, when the principles of Reusser's model for cognitive tools are examined closely, it becomes apparent that they are precisely the kinds of elements that Derry and Lajoie (1993) argued are descriptive of theorists who occupy the middle ground of the model/non-modeller continuum.

However, the type of computer programs used, the reasons for using them, the nature and quality of the software, and assessing whether students had any measurable gains in concept attainment are important considerations. Thus, a critical issue for the effective use of computers in a given subject area is the specificity of the software program as it relates to the nature of the problems being addressed. The tight relationship required between the software used and the nature of the problem to be solved is why the "tool" metaphor is an appropriate one in the case of computer use in education. Tools are highly specialized instruments that when used in the right way, with the proper training, at the right time, and on an appropriate problem can lead to the construction of desired outcomes in a manner that is effective and efficient.

As discussed next, computer simulations appear to meet most of the critical criteria noted by Reusser (1993) as elements of an effective computer tool. In addition, as Derry and Lajoie (1993) suggested, computer simulations are examples of programs that have epistemological characteristics that put them within the middle camp. That is, computer simulations can provide structured learning scenarios without unduly constraining intentional learners who are motivated to explore the multiple dimensions of complex problems that simulations can create (Casti, 1997).

**Simulations as Cognitive Tools for Learning in Science**

Thomas and Hooper (1991) argued that in order for simulations to be effective as learning tools, it is important to be precise about what is meant by the term "simulation". The researchers delineated two types of simulations, pure and impure. A computer
program was considered a pure simulation if it could be described in the following manner. First, the program had to model a real or theoretical system that could be manipulated by the user. Thus, various states of the system changed as user input varied. Second, a pure simulation had to have some goal or outcome that, as a result of correct user inputs and manipulations, could be achieved. In other words, users are presented with some obtainable outcome and they must interact with the computer to produce a solution that satisfactorily achieves that goal. Third, pure simulations were not considered synonymous with flexible tutorials (i.e., ITS). That is, pure simulations do not provide feedback about how or what actions a user must take. Thus, overall, pure simulations represent or model some complex system. Ultimately, understanding how such a system operates should be the focus or goal of the learner’s efforts.

On the other hand, impure simulations were defined as programs that contained various mixes of common computer-mediated approaches to learning. For example, a simulation that included some tutorial-type feedback based on users’ input or that did not specify a goal or outcome that users were to work towards was considered impure. In short, Thomas and Hooper (1991) suggested that any computer program that did not meet the criterion for a pure simulation, was by definition, an impure simulation.

Using the above definitions, Thomas and Hooper (1991) reviewed 29 simulations (21 pure, 6 impure, 2 unclassified) and developed four broad descriptive categorizations of a simulation’s instructional function: 1) Experiencing, 2) Informing, 3) Reinforcing, and 4) Integrating. Experiencing simulations were programs that preceded formal instruction and were used to motivate learners, organize information, provide concrete examples of domain specific content, or expose misconceptions. The researchers suggested that experiencing simulations were functionally equivalent to Ausubel’s “advanced organizer”. Informing simulations were programs that used the computer to transmit information to students in a way that supplemented or replaced a textbook or lecture. Reinforcing simulations were essentially equivalent to drill and practice programs. That is, the user interacted with the program in a way that served to strengthen the specific learning objective(s) of the simulation. Integrating simulations were programs that required users to learn several concepts separately and then apply those concepts in an coherent fashion in order to solve specific problems.

Thomas and Hooper (1991) found that pure simulations were most effective in supporting conceptual change when they functioned as either experiencing or integrating
instructional tools. Impure simulations were most effective in contributing to conceptual change when used as tools for informing and reinforcing instruction. The researchers also noted in their review that the effects that a specific simulation had on learning may not be revealed by traditional tests of knowledge. Instead, the educational effectiveness of a simulation, especially experiencing simulations, was more likely to be apparent when assessment of transfer and application were used as measures of learning. Thomas and Hooper's classification scheme is useful because it provides some guidance for how, why and when to employ a specific simulation. For example, if a program exhibits characteristics that define it as experiencing, then it may be utilized best as an introduction to the conceptual domain being studied rather than as the focus or central component of a unit. Again, the tool metaphor is appropriate because Thomas and Hooper (1991) are advocating a close match between the nature of the program itself and the educational objectives expected of learners.

There are several other possible dimensions and classification schemes that can be considered when examining the nature of simulations as learning tools. Casti (1997) used two broad categories as a means of classifying simulations. One category discriminates between simulations that can be viewed as either “top down” or “bottom up”. Top down simulations involve the use of “aggregated quantities” as the variables that determine the outcome of the simulation. For example, simulated economies often make use of variables that are compilations of separate quantities (e.g., gross domestic product, per capita spending, population size) as predictive determinants of the overall direction (i.e., growth vs. decline) of the economy. In contrast, “bottom up” simulations use knowledge of how individual “agents” (e.g., organisms, automobile drivers, stock traders, atoms) are likely to behave, alone and in interactions with other agents, to guide the processes of the simulation. Bottom up simulations are distinct from top down simulations in that they can produce “emergent phenomena”. Emergent phenomena are higher-level characteristics or patterns of activity that result from the interactions of individual agents and that are difficult (or impossible) to predict from knowledge of the characteristics of the agents themselves. One simple example of emergence is the unexpected properties of water (H₂O, a non-flammable liquid) that results from the bonding of its elements, hydrogen and oxygen (both gaseous and combustible).

The other important category that Casti (1997) uses for classifying a simulation is the extent to which it satisfies the criterion of being a good scientific model. As such,
simulations can be judged against five different properties (see Table 5). Thus, like most scientific models, a simulation's value depends heavily on the use to which it will be put. Casti (1997) uses several examples where simulations of various systems (traffic patterns in a US city, evolutionary processes, stock prices) are described in terms of his five criteria. For educational purposes, the value of Casti's scheme is that it provides a means of helping learners understand both the nature of science and the ways simulations can be used by learners who are trying to understand complex science concepts and systems.

Table 5.
Five criteria of a good scientific model that can be used in describing the nature of a computer simulation (Adapted from Casti, 1997).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fidelity</td>
<td>The model's ability to represent reality to the degree necessary to answer the questions for which the model was constructed.</td>
</tr>
<tr>
<td>Simplicity</td>
<td>The level of compactness of the model, in terms of how &quot;small&quot; the model is in things like the number of variables, complexity of interconnections among subsystems, and number of ad hoc hypotheses assumed.</td>
</tr>
<tr>
<td>Clarity</td>
<td>The ease with which one can understand the model and the predictions/explanations it offers for real-world phenomena.</td>
</tr>
<tr>
<td>Bias-free</td>
<td>The degree to which the model is free of prejudices of the modeller having nothing to do with the purported focus or purpose of the model.</td>
</tr>
<tr>
<td>Tractability</td>
<td>The level of computing resources needed to obtain the predictions and/or explanations proffered by the model.</td>
</tr>
</tbody>
</table>

Windschitl (1998) provided another scheme for classifying simulations. Windschitl's categories were developed in the context of a technologically based biology program where over 1000 students a week used simulations related to the study of the human cardiovascular system, photosynthesis, population genetics and other biologically based phenomena. Three broad categories were used to classify the various simulations: 1) Kinesthetic, 2) Procedural, and 3) Process. *Kinesthetic* simulations were those that required users to learn how to perform a certain set of actions to accomplish a particular goal. For example, a simulation that required learners to dissect a virtual frog or, more commonly, flight simulators, were described as kinesthetic simulations. *Procedural* simulations were similar to kinesthetic programs but required more applied knowledge of the system under investigation. For example, simulations that required learners to set up a virtual experiment (e.g., distillation apparatus) and then conduct it using idealized parameters were typical of procedural simulations. These types of programs were
especially suited for potentially hazardous or expensive experiments. Process simulations were those that modelled complex, interactive phenomena not easily observed in natural settings. Photosynthesis, evolution and cardiovascular function were examples of systems that were modelled using process simulations.

Of the three types of simulations described above, Windschitl (1998) suggested that process simulations were likely to provide the greatest opportunities for conceptual change. These simulations allowed users to change important variables and components of the model and encouraged them to explore the system in a way the other types of simulations did not. In short, process simulations promoted the following cognitive activities:

Most well-constructed process simulations can support the practice of inquiry skills such as observation, measurement, hypothesis generation, manipulation of variables, and inference, as well as broader critical thinking skills such as understanding correlation versus cause, identifying complex patterns in data, and creating models of phenomena by students. At the risk of oversimplification, any exercises that thoughtfully place these exploratory intellectual demands upon the student are more likely to be effective than those that ask the student to simply describe phenomena or "fill in the blanks" in a cookbook laboratory exercise (Windschitl, 1998, p. 93).

Snir, Smith, and Grosslight (1995) proposed to classify simulations based on how analogies are used in science. Snir et al.'s scheme evolved from work with simulations in the physical sciences. Their goal was to use computer simulations as a means of making explicit tacit assumptions and relations between the phenomenon itself (e.g., flotation) and the scientific theoretical/conceptual model that explains it (e.g., density) via the kinds of analogies that are frequently used in such situations. Typically, scientific analogies attempt to map or connect the referent objects from separate domains by using both the attributes of the objects and the relationships among those objects. For example, the kinetic theory of gases uses an analogy between billiard balls and molecules of different gases. Attributes that might apply to both sets of objects from their respective domains could be things such as round, difficult to break apart, and move easily. Relationships among the objects might include the nature of collisions that result with a given level of energy, the nature of the interaction among objects located in different regions of space, and how objects are affected by different angles of collision.
Thus, Snir et al. (1995) suggested that simulations could be categorized along two dimensions: 1) Object-attribute simulations, and 2) Relations simulations. Object-attribute simulations provided the concrete, readily observable characteristics of a particular class of objects related to a given phenomenon. These types of simulations served to motivate learners with visually appealing displays and helped them learn about those characteristics of the objects that were most relevant to the system under investigation. In contrast, relations simulations sought to reveal how the objects in a system interacted with one another and made the dynamic nature of such interactions more apparent. For Snir et al. (1995), many simulations failed to connect these two dimensions. Instead, they suggested that good simulations were ones where the program designers:

... add visual representations of the concepts used in explaining a specific phenomenon (the theoretical level) to the representation of the observable features of the objects (the concrete level). This enables students to observe, simultaneously on the same screen, two levels of thinking about the same phenomena and to live in (or experience) the conceptual space in which the expert thinks (Snir et al., 1995, p. 112).

Thus, those simulations that made explicit the connections between the concrete attributes of the objects in a system with the theoretical laws and principles that govern the interactions of those objects in a given system were deemed "conceptually enhanced simulations". Snir et al. (1995) provided evidence that these types of simulations were very effective aids in improving concept attainment in grade six, seven, and eight students studying units on mass, density and flotation.

It is important to point out that most classification schemes are rarely meant to represent rigidly discrete categories. Rather, a continuum of those elements most characteristic of each broad category is the most useful way to view any taxonomic system. As such, Weller (1996), in an extensive review of the use of computers in science education, suggested that simulations could be broadly categorized as instructional tools that supported conceptual change. Weller noted that such programs could be utilized by educators because they could help students with a problem common to learning in science; many students possess nonscientific preconceptions that tend to be very resistant to change. Thus, simulations were programs described as tools that helped
to expose existing misconceptions and then facilitated student progress towards the more scientifically accurate conceptions of the domain-specific problem.

Weller (1996) did not expand on those specific characteristics of a simulation that putatively operated to promote conceptual change. Rather, a simulation was deemed to promote learning to the degree that the program met the criteria suggested by Strike and Posner (1992) as important for encouraging such change. These factors included the ability of the simulation to evoke a user’s dissatisfaction with current conceptions, and to provide a new conception that was intelligible and plausible to the user. As Derry and Lajoie's (1993) non-modellers would suggest, a computer simulation, by itself, cannot “know” of every conceivable misconception that a user could bring to the keyboard. Instead, the simulation needs only to present data or system scenarios that, if interpreted correctly by users, create a reasonable probability that learners will become aware of, and then acknowledge, a disparity between the conceptions they hold and the ideas being explored within the simulation. How and if a user seeks to resolve such a disparity will depend heavily on the interaction between the teacher, the program, the user, and the problem being investigated (De Jong & Van Joolingen, 1998; Stanovich, 1999; Strike & Posner et al., 1992).

Weller (1996) makes a notable observation concerning the studies he reviewed. He suggested that although much of the research regarding the use of computers was “aimed at expanding our knowledge about science learners and how they learn best, many did not aim to investigate comprehensive instruction in the products and processes of science” (Weller, 1996, p. 481). For example, more than a third of the studies he cited sought to compare the efficacy of one delivery medium over another (e.g., computers vs. traditional instruction). Because of the methodological difficulties in controlling extraneous factors in media comparison studies, Weller suggested that science education research could benefit more from studies that focused on comparing instructional methods (e.g., pacing, breadth versus depth of content, individual versus group work) and the effects such methods have on facilitating science learning.

Simmons and Lunetta (1993) provided a good example of research that investigated this instructional methods emphasis. Their study explored how a simulation of Mendelian genetic principles affected novices’ and experts’ problem-solving reasoning. Ten novices (high school students taking advanced biology) and three experts (individuals holding a Ph.D. in biological science) were asked to determine the
inheritance patterns of a specific genetic trait (i.e., colour striping) in virtual cats. Subjects were asked to “think aloud” as they progressed through the problem and to use the simulation to generate as much data as they felt necessary to arrive at a conclusion.

Three important methodological aspects of Simmons and Lunetta’s (1993) study are noteworthy. First, with the help of the computer simulation, subjects were able to do multiple iterations of experiments, in a timely fashion, to produce their data. That is, if there was something that subjects felt unsure of, or if they wanted to check their results against data produced earlier, they could run the simulation as often as they liked. Second, the simulation, combined with the “think aloud” approach, resulted in exposing misconceptions not only in students but in two of the experts as well. Specifically, the experts were incorrectly confusing actual and predicted Punnett square ratios. That is, the experts appeared to confuse the results generated from a sample with idealized results predicted by mathematical models of inheritance. As an aside, this difficulty is exactly the kind of “generalization problem” described by Tversky and Kahneman (1981).

We submit that people view a sample randomly drawn from a population as highly representative, that is, similar to the population in all essential characteristics. Consequently, they expect any two samples drawn from a particular population to be more similar to one another and to the population than sampling theory predicts, at least for small numbers (Tversky & Kahneman, 1981, p. 269).

The one expert that did not commit this error “generated a large sample and compared actual and predicted ratios of outcomes” (Simmons & Lunetta, 1993, p. 162).

Last, it seems that the nature of the simulation itself was instrumental in bringing about some of the performance gains observed in the study. Simmons and Lunetta (1993) noted that the simulation required subjects to: 1) generate their own hypotheses, 2) apply scientific principles, 3) decide which variables to control, 4) gather, record, analyze, and interpret data they generated, and 5) make inferences to support or reject hypotheses. Although Simmons and Lunetta (1993) did not classify their program as belonging to any particular type or class of simulation, their observations about the kinds of cognitive activities it engendered in users were very similar to those reported by Windschitl (1998).

In contrast to Simmons and Lunetta’s (1993) instructional method study, Hounshell and Hill (1989) conducted a media-comparison study that explored students'
achievement and attitudes in a high school biology course. Seventy-six students were randomly assigned to different sections of the course. Students in the experimental group (computer-loaded sections) made extensive use of biological simulations (over 60% of all class time). Students in the control group received instruction in the traditional manner (lectures and labs) using the standard system-wide biology curriculum. Briefly, the results indicated that students in the experimental group had significantly higher achievement scores and had significantly more positive attitudes towards biology than did students in the control group.

Two important details of Hounshell and Hill's (1989) study are noteworthy. First, as Weller (1996) argued, an equally plausible alternative explanation for the researchers' results could be that more effort was devoted to developing quality instructional methods for the simulations compared to the traditional presentations of the same material. Thus, students in the experimental group may have been exposed to more effective instructional methods (not necessarily a more effective instructional media) compared to students in the control group. Second, Hounshell and Hill indicated that over 100 biology-related software programs were available to students in the experimental group. Most notably, of these 100 programs, not a single simulation listed explored the concept of evolution. In light of Dobzhasky's (1973) dictum, "Nothing in biology makes sense except in the light of evolution", the fact that not one program in their study was devoted to evolutionary concepts is an oversight that deserves some research attention.

In the context of studies that have examined the use of simulations focusing on evolutionary concepts, there were several investigations that described the development and operation of the simulations themselves (Duhrkopf, 1991; Hodgson & Murphy, 1984; Marco & Lopez, 1993; Murphy, 1984; Reiss & Jameson, 1984; Sepe, 1988; Thompson, 1988). All of these studies explained how their particular simulation was designed, the details of how the simulation modelled (to various degrees) events in the real world, how students interacted with the program, and some assessment of how easy the program was to use. However, none of the above mentioned studies reported how the use of the evolutionary simulation influenced students' learning of those concepts.

The only study reviewed that examined the effects of a biological simulation on student learning was one conducted by Tylinski (1994). This research compared the achievement scores of grade-nine students examining earthworm physiology. The control group participated in the traditional approach of learning about earthworms which
included dissection of a specimen. The experimental group received similar instruction but, instead of real dissection, used a simulation to explore earthworm physiology. Tylinski (1994) reported that the group of students using the simulation had significantly lower achievement scores on a measure of knowledge about earthworm physiology when compared to the control group which performed the dissection.

Notably, Tylinski's (1994) simulation study was about a process (i.e., dissection) that, by comparison, is easy to study and is concrete. That is, this investigation was designed because of the researcher's beliefs about the implications of using animals in research and not because of the intractable nature of the problem as a complex system to investigate. Dissecting a worm is clearly a very tangible exercise, and students can use all five senses when exploring earthworm physiology via dissection. Thus, results that showed lower performance in the simulation group is not surprising. Parenthetically, medical researchers are using highly sophisticated simulations to prepare surgeons for complex operations. However, there is an obvious difference in the kind of simulations used in medical research and the level of knowledge already possessed by the surgeons before using such programs.

Summary

Computers are a relatively new technological innovation in educational settings. Because of this, research to support their value is slowly beginning to reveal how computers can best be utilized to aid in student learning. One useful way of trying to understand how computers can be used more effectively is to view computers as cognitive tools. The tool metaphor suggests computers can be used most effectively when they are employed for specific tasks, at the appropriate point in a curriculum, and for solving specific problems.

There is some theoretical debate about the degree to which the computer should control what is learned and when. At one end of this continuum is a group of researchers who suggests learning can best be accomplished if the computer dictates the learning sequence. The other theoretical camp suggests that control must remain with the learner and thus, the computer should be a tool that allows students to explore and share ideas in a social context of learning. A third group of investigators suggests that some elements of both positions are warranted.
One type of computer program that exemplifies this middle position is simulations. Simulations are programs that require a user to interact with the computer in a way that will produce some goal or outcome. Several ways of classifying simulations have been suggested. Most categorization schemes rely on describing how a user interacts with the program, identifies the goal or purpose of the simulation, and classifies the degree to which certain types of cognitive activities are required of the learner. Simulations have been shown to support learning especially for tasks that require transfer of knowledge or application of concepts. However, methodological difficulties in studies claiming to show improved learning with the use of simulations preclude definitive conclusions about their effectiveness.

Simulations have been used in science education with some reported success. Notwithstanding some methodological difficulties, simulations have been used to advance learning in genetics and in several areas related to general biology. However, no research studies could be located that detailed the effectiveness of simulations that were specifically designed to enhance learning of evolutionary concepts per se. Given the central position this theory holds in the biological and social sciences (Wilson, 1998), there is a need to explore this computer-based approach to learning in this context.
Chapter 3
Method

When spiders unite they can tie down a lion - Ethiopian Proverb

Overview

A case study of 19 pre-service Intermediate/Senior science teachers was used to explore how the use of a computer simulation of basic evolutionary processes in combination with small-group discussions affected their perspectives on evolution. Both qualitative and quantitative methods were incorporated in the procedures and the analyses.

Specifically, the qualitative methods included an examination of the small group discussions for emergent themes as participants interacted with the computer simulation. The group discussions were guided by a series of questions regarding specific evolutionary concepts. Additionally, at the end of the study, participants were asked to respond to semi-structured interview questions. These questions provided participants with an opportunity to express their ideas about two applied evolutionary problems, to explain to the researcher how they felt the simulation had been helpful or confusing to them in trying to understand basic evolutionary concepts, and to offer any general comments about the study per se.

The quantitative methods involved analyses of the information gathered from four separate surveys: 1) Evolution Knowledge Survey (EKS), 2) Intentions to Teach Evolution Questionnaire (ITEQ), 3) Nature of Science Survey (NOSS), and 4) Resource Use Survey (RUS). Basic descriptive statistics (e.g., mean, standard deviation, range, correlation) were the primary metrics used to explain the data. Inferential statistics were not used in this investigation. In addition, where appropriate, some summary descriptive statistics were used to complement the qualitative analyses noted above.

Participants

The participants in this investigation were 19 Intermediate/Senior pre-service science students enrolled in a teacher education program at a major Ontario university. Initially, students who entered the intermediate-senior pre-service science program at the university (n=118) were randomly assigned to one of five classes of roughly equal sizes which were then allocated to one of three professors. One of these professors was
approached and asked if the students in her class could be solicited to participate in the study. This class was composed of 24 students and after inviting their participation in the study, 22 agreed to take part. Following the first phase of the study (see Table 6, p. 51), three participants dropped out. Two participants cited overloaded schedules and the third person left due to illness. No information gathered from individuals who withdrew from the study was used in any of the results. Thus, a total of 19 participants, 15 females and four males, completed all phases of the study. Sex of the participants was not of interest in this investigation, so all subsequent data can be assumed to be collapsed across this variable.

Participants were asked to provide responses to two self-report variables: 1) the number of full-time, university biology courses taken, and 2) their principal “teachable” subject. Figure 2 provides a breakdown of these two variables for all 19 participants. No other demographic information was collected from participants. No information was gathered from the two individuals in the class who initially chose not to participate.

Figure 2.
Self-reported number of full-time university biology courses for all 19 participants as a function of declared principal teachable subject.

<table>
<thead>
<tr>
<th>Teachable</th>
<th># of full-time biology courses</th>
</tr>
</thead>
<tbody>
<tr>
<td>GenSci (n=13)</td>
<td>9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0</td>
</tr>
<tr>
<td>P&amp;HE (n=2)</td>
<td>9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0</td>
</tr>
<tr>
<td>Math (n=3)</td>
<td>9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0</td>
</tr>
<tr>
<td>Chem (n=1)</td>
<td>9.0, 8.0, 7.0, 6.0, 5.0, 4.0, 3.0, 2.0, 1.0</td>
</tr>
</tbody>
</table>

Notes: * GenSci = General science, P&HE = Physical and Health education, Chem = Chemistry

* Two participants with Math as their principal teachable subject reported taking no university biology courses.
Study Phases and General Design Rationale

The study was conducted in six different phases over a 13 week period. The phases of the study and the activities associated with each phase are outlined in Table 6. The investigation took place over this time span in order to accommodate the participants' schedules with respect to their course work in the Bachelor of Education program and their practice teaching assignments. Additionally, time allotments and the nature of the activities in phases two, three and four were designed to imitate some of the methods and constraints that a practicing teacher might face when confronted with the prospects of creating a lesson on a topic that they have not taught before. These details are discussed in greater depth in the procedure section below, however, they will be outlined briefly here.

Table 6.
Phases of the study conducted over a 13 week period, a brief description of the activities associated with each phase, and the focus or questions addressed at each phase.

<table>
<thead>
<tr>
<th>Phase (Time period)</th>
<th>Activity</th>
<th>Theoretical Focus/Questions</th>
</tr>
</thead>
</table>
| 1. Baseline (Week 1) | - Administer questionnaires  
- Form dyads/triads | - Assess participants' knowledge of evolutionary concepts (Quantitative description)  
- Exploration of possible relationships among knowledge of evolution, science epistemology and intentions to teach evolution (Quantitative description) |
| 2. Simulation for familiarization (Week 2) | - Run the computer simulation  
- Audio tape group discussions | - Exploration of how participants in small groups talk about evolutionary concepts when using the simulation as the reference for their discussions (Qualitative description) |
| 3. Lesson Plan (Weeks 3 - 9) | - Distribute resources  
- Prepare lesson plan on natural selection | - Is there any evidence that the process of creating a lesson plan leads to improved understanding of the concept under consideration? (Quantitative description) |
| 4. Simulation for exploration (Week 10) | - Run the computer simulation  
- Audio tape group discussions | - Exploration of how participants in small groups talk about evolutionary concepts when using the simulation as the reference for their discussions (Qualitative description) |
| 5. Concept Map (Week 10) | - Complete concept map  
- Collect and grade lesson plans | - How do participants link key elements of evolutionary theory? (Qualitative description) |
| 6. Final interviews (Week 13) | - Conduct final interviews  
- Complete Resource Use Survey | - Assess participants' knowledge using applied evolutionary problems (Qualitative description)  
- What are participants' perspectives on using the simulation? (Qualitative description)  
- What resources used in the study did they find most useful? (Quantitative description) |
Time and exemplary curriculum materials are two resources often in very short supply for practicing teachers, especially for the topic of evolutionary biology (Swarts, Anderson, & Swetz, 1994). In phases two and four, the time allotted for the activity (about 1.25 hours for each phase) was a calculated constraint because this is roughly how much time teachers will have to devote to teaching a high school lesson. In phase three, however, the time allotted for preparation of the lesson plan was maximized so that participants had sufficient opportunity for learning about and generating a quality lesson on natural selection. Furthermore, participants were provided with several exemplary curriculum materials on natural selection in order to assist them in creating their lessons (e.g., Dennett, 1995; McComas, 1994; National Academy of Sciences, 1998).

Surveys and the Simulation

Four different surveys and one computer simulation were used in this investigation. The questionnaires used were: 1) the Evolutionary Knowledge Survey (EKS), 2) the Nature of Science Survey (NOSS), 3) the Intentions to Teach Evolution Questionnaire (ITEQ), and 4) the Resources Used Survey. The simulation used in the investigation is called MicroAnts (Wright, 1993). A description of all the materials used in the study will be discussed next.

Evolutionary Knowledge Survey (EKS). The EKS (Appendix A) is a paper and pencil survey designed to assess participants' knowledge of basic evolutionary concepts (Jensen & Finley, 1996). The EKS was used in this investigation for three purposes: 1) to assess participants' understanding of basic evolutionary concepts, 2) to assign a participant to an appropriate dyad or triad on the basis of their EKS score, and 3) to explore possible relationships among participants' understanding of evolutionary concepts, their perspectives on science epistemology, and their intentions to teach evolutionary concepts with their students.

The EKS consists of 28 questions or statements divided into five sections. The first section contains seven questions, each of which has two parts. Part 'a' of each question requires subjects to use a 5-point Likert-type scale for their response and part 'b' asks subjects to use a sentence or two to justify the answer given in part 'a'. The questions in this section test for one's broad conceptual understanding of evolutionary principles using ducks' webbed feet as the focus for the questions.
The second section consists of four, two-part questions (i.e., items 8 - 11). Part 'a' of each question is worded in a multiple choice format and part 'b' asks participants to use a sentence or two to justify the answer given in part 'a'. Item 11 on the EKS (which replaced a conceptually awkward question in Jensen and Finley's (1996) original scale) asks participants to list evidence that supports (part 'a') and refutes (part 'b') the theory of evolution by natural selection and to use a sentence or two to explain their answer. This substitute question was the only modification made to the original scale. The purpose of questions eight to eleven was to test for broad conceptual understanding of evolutionary principles using applied examples common to most people's experiences.

The third section of the EKS consists of a single question (item number 12). Part 'a' of this item is multiple choice and part 'b' asks subjects to use a sentence or two to justify the answer chosen in part (a). The purpose of question 12 was to examine subjects' understanding of the word "fitness".

The fourth section, item numbers 13 to 16, consists of two types of questions. The first type of question (i.e., items 13 to 15), asks subjects to explain the reasons why certain biological adaptations are evident in a specific species. The purpose was to assess participants' applied understanding of how natural selection operates to produce adaptations in a population of organisms. The second type of question in this section, item 16 (A to K), asks participants to use a four-point scale to assess whether they think the statement is, correct (1), mostly correct (2), not completely correct (3), or is wrong (4). Then, subjects are asked to provide one or two sentences to justify the answer given in part one. The purpose of question 16 (A to K) was to explore participants' ideas concerning common misconceptions they may have regarding the mechanisms, purposes and outcomes of evolution.

Finally, the fifth section of the EKS contains a single question. This item asks subjects to rate, on a 5 point scale, the extent to which they believe Darwin's theory of evolution by natural selection is true and to explain the reason for their choice.

Jensen and Finley's (1996) scale was originally designed to assess grade seven and eight students' understanding of evolutionary concepts. Thus, the items on the original scale were constructed so that the wording and examples would be age appropriate. Prima facie and content validity of the scale were assessed by the input of two evolutionary biologists during the scale's construction. The biologists examined the items and provided feedback on item wording and suggested changes to item choice to
ensure a variety of theories about evolution were represented. Jensen and Finley (1996) obtained additional support for the validity of their instrument by examining subjects' written responses to the questions and from responses obtained in clinical interviews with their subjects. The researchers reported that their participants provided similar types of answers for written and oral responses. Moreover, Jensen and Finley (1996) found that their instrument produced a good range of scores and that the reliability for the items was good. Inter-rater reliability was reported to be above 90%.

Additional attempts were made to assess the validity of Jensen and Finley's (1996) scale as it was implemented in this study. The items on the EKS (Appendix A) were examined by a zoologist and an instructor of evolutionary psychology from two local universities. Both experts were asked to provide answers to all questions on the survey. Of the 27 separate questions on the EKS for which evolutionary content knowledge is solicited, the two experts agreed on their answers to 25 items (93%). The two items that the experts disagreed on were question 6 in section 1 and question 16K in section 4. Although both experts provided very different answers to question 6, they agreed that the wording of the question was ambiguous and potentially misleading. Item 16K was not considered a content question by one of the experts whereas the other expert made no comment regarding the nature of this item's intent. Other possible modifications to the EKS and methods of scoring it were discussed with the first author of the original scale to ensure the validity and reliability of the scale's items remained intact (Jensen, 1998, personal communication).

Consequently, a participant's total EKS score was determined by adding the number of correct responses to the following 20 items: 1, 2, 3, 4, 5, 7, 8, 9, 10, 12, 16A-J (Appendix A). A participant's answer to an item was judged correct in one of two ways. First, a response was considered correct if a participant circled the appropriate letter or numeric response for an item (i.e., 1-3(5); 4,5,7(1); 8(c); 9(c); 10@); 12(d); 16A-J(4), see Appendix A) regardless of their written response.

Second, if a participant did not circle the correct numeric or letter response, an item was scored as correct if a participant provided a written response that was deemed "qualified correct". To assess whether an answer was considered qualified correct, the author and one of the experts independently scored all written answers that were not circled correct. For all of the written answers to the 20 questions, there was 94% agreement on how a particular response should be scored (correct or incorrect). For those
Nature of Science Survey (NOSS). The NOSS (Appendix B) is a paper and pencil survey that was designed to examine participants' perspectives on science epistemology. The purpose of using the NOSS was to explore the possible relationships between participants' understanding of evolutionary concepts and their perspectives on science epistemology. The NOSS is composed of two parts. Part A is a subset of questions from the Views on Science-Technology Society (VOSTS) survey developed by Aikenhead and Ryan (1992). The statements on the VOSTS were designed to explore a wide variety of attitudes towards the nature of science and technology and science epistemology. The VOSTS was created exclusively as a qualitative, narrative instrument and was not meant to be assessed in terms of quantitative criterion such as reliability or validity coefficients (Aikenhead, 1998, personal communication). Nonetheless, Botton and Brown (1998) investigated all of Aikenhead and Ryan's (1992) original VOSTS items for their reliability. Of the 22 items on the VOSTS designated as relating to science epistemology, 20 items were found to have acceptable reliability (Pearson chi-squared = .72). These 20 items were used in Part A of the NOSS for this investigation.

Part B of the NOSS (Appendix B) is a questionnaire developed by Nott and Wellington (1993). Their scale consists of 24 items in which users respond to each item by indicating on a 11-point Likert scale the degree to which they agree with a statement. Thus, responses can vary from strongly disagree (-5) to strongly agree (5). A response of '0' indicates a belief that the statement under consideration was sometimes true and sometimes false. The Nott and Wellington questionnaire produces a profile for each user on five dimensions. Table 7 gives a description of each of the dimensions as outlined by Nott and Wellington (1993).

The Positivist-Relativist (PR) sub-scale is composed of two unique items (1, 20) and six shared items (3, 12, 14, 16, 18, 21). Scores on the PR sub-scale can range from -40 (Positivist) to +40 (Relativist). The Inductivist-Deductivist (ID) sub-scale has four unique items (5, 11, 19, 23). Scores on the ID sub-scale can range from -20 (Inductivist) to +20 (Deductivist). The Decontextualist-Contextualist (DC) sub-scale has five unique
Table 7. Descriptions of Nott and Wellington's (1993) five dimensions as assessed on their Nature of Science Survey.

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positivists vs. Realists (PR)</td>
<td><strong>Positivists</strong> believe strongly that scientific knowledge is more 'valid' than other forms of knowledge. The laws and theories generated by experiments are our descriptions of patterns we see in a real, external, objective world. To the positivist, science is the primary source of truth. Positivism recognizes empirical facts and observed phenomena as the raw material of science. The scientist's job is to establish the objective relationships between the laws governing the facts and observables. Positivism rejects inquiry into underlying causes and ultimate origins. <strong>Realists</strong> deny that things are true or false based solely on an independent reality. The 'truth' of theory will depend on the norms and rationality of the social group considering it as well as the experimental techniques used to test it. Judgements as to the truth of scientific theories will vary from individual to individual and from one culture to another; i.e., truth is relative, not absolute.</td>
</tr>
<tr>
<td>Inductivists vs. Deductive (ID)</td>
<td><strong>Inductivists</strong> believe that the scientist's job is the interrogation of nature. By observing many particular instances, one is able to infer from the particular to the general and then determine the underlying laws and theories. According to inductivism, scientists generalize from a set of observations to a universal law 'inductively'. Scientific knowledge is built by induction from a secure set of observations. <strong>Deductivists</strong> believe that scientists proceed by testing ideas produced by logical consequences of current theories or of their bold imaginative ideas. According to deductivism (or 'hypothetico-deductivism'), scientific reasoning consists of the forming of hypotheses which are not established by the empirical data but must be suggested by them. Science then proceeds by testing the observable consequences of these hypotheses (i.e., hypotheses are directed or led by hypotheses - they are theory-laden).</td>
</tr>
<tr>
<td>Decontextualists vs. Contextualists (DC)</td>
<td><strong>Decontextualists</strong> hold the view that scientific knowledge is independent of its cultural location and sociological structure. <strong>Contextualists</strong> hold the view that the truth of scientific knowledge and process is interdependent with the culture in which the scientist lives and in which it takes place.</td>
</tr>
<tr>
<td>Content-oriented vs. Process-oriented (CP)</td>
<td><strong>Content-oriented</strong> individuals think that science is characterized by the facts and ideas it has and that the essential part of science education is the acquisition and mastery of this body of knowledge. <strong>Process-oriented</strong> individuals see science as a characteristic set of identifiable methods/processes. The learning of these is the essential part of science education.</td>
</tr>
<tr>
<td>Realists vs. Instrumentalists (RI)</td>
<td><strong>Realists</strong> believe that scientific theories are statements about a world that exists in space and time independent of the scientist's perceptions. Correct theories describe things which are really there, independent of the scientists; e.g., atoms. <strong>Instrumentalists</strong> believe that scientific theories and ideas are fine if they work, that is, they allow correct predictions to be made. They are instruments which we can use but they say nothing about an independent reality or their own truth.</td>
</tr>
</tbody>
</table>

items (2, 6, 8, 13, 22) and three shared items (3, 16, 18). Scores on the DC sub-scale can range from -40 (Decontextualist) to +40 (Contextualist). The Content-oriented-Process-oriented (CP) sub-scale has five unique items (7, 9, 15, 17, 24). Scores on the CP sub-
scale can range from -25 (Content) to +25 (Process). The Realist-Instrumentalist (RI) sub-scale has two unique items (4, 10) and three shared items (12, 14, 21). Scores on the RI can range from -25 (Realist) to +25 (Instrumentalist). Those items that are reversed-keyed can be found in Nott and Wellington (1993). It should be noted that an error was detected for item eight in the scale as it was originally published (Nott & Wellington, 1993). A revised version of the scale was obtained from the authors and the error was corrected.

Nott and Wellington (1993) suggested that the profile produced from their instrument should not be taken as a strictly valid indication of one's perspective regarding the nature of science. Rather, the authors indicated that the scale was to be used as a way to encourage individuals to reflect on their views regarding the nature of science and as an impetus for generating discussion related to the philosophy of science in general.

**Intentions to Teach Evolution Questionnaire (ITEQ).** The ITEQ (Appendix C) is a paper and pencil survey that was designed to assess participants' intentions to teach evolutionary concepts with their students. This questionnaire was developed by the author for this investigation for the purposes of: 1) examining the importance of beliefs and how they affect participants' understanding of evolution (Cobem, 1994; Smith 1994), and 2) exploring for possible relationships between participants' intentions to teach evolutionary concepts in the classroom and their understanding of evolutionary concepts.

The construction of the scale's items was based on the Theory of Planned Behaviour (Ajzen, 1985). The Theory of Planned Behaviour posits that an individual's intentions are the best predictor of what an individual will actually do. The theory has received empirical support in several different domains (Crawley & Koballa, 1994; Lumpe, Czerniak & Haney, 1998; Petty & Cacioppo, 1981). In the context of this investigation, the behaviour in question is pre-service science teachers' intentions to teach the theory of evolution by natural selection. A participant's intention score is calculated by combining responses to six unique sub-scale variables (see Figure 1, p. 28). Because this was the first time this scale had been used empirically and the purpose of this questionnaire was primarily exploratory, no attempts were made to obtain reliability or validity data for the individual items or for the test as a whole.

**Resources Used Survey (RUS).** The RUS (Appendix D) is a paper and pencil survey designed by the author to assess which resources participants used in the study and the extent to which they found these resources useful in helping them to learn about
evolutionary concepts. There was a total of eight different resources/activities that participants could have used throughout the study. All possible combinations of these eight resources were arranged in pairs. Subjects were asked to judge which resource in each pair they found most useful or helpful in trying to learn about evolutionary concepts. Analysis of participants' judgements was based, in part, on an analytical technique called dual scaling (Nishisato, 1994). This statistical procedure allows categorical data of this type to be analyzed for general response patterns that are difficult to uncover using traditional inferential approaches (Nishisato, 1994).

The Simulation. Several evolutionary simulations were reviewed, including "Evolution: The game of intelligent life" (Discovery Communication, 1997), "SimLife: The genetic playground" (Maxis, 1997), and several in Prata (1993), before selecting "MicroAnts" (Wright, 1993). The MicroAnts simulation is a program designed to model basic evolutionary phenomena in two populations of virtual ants and was selected for several reasons. First, the program is a good example of a "bottom" up simulation (Casti, 1997; Epstein, & Axtell, 1996). That is, it makes use of simple, interacting virtual organisms who can differ on various individual attributes and whose behaviours are governed by rules and constraints among the organisms and the virtual environment they inhabit. The result of all these elements and rules operating together is a reasonable facsimile of the kinds of emergent phenomena and concepts that form the foundation for understanding the vast majority of natural evolutionary principles (Casti, 1997).

Second, most biologists consider the gene as the central component of contemporary theories of evolution (Ayala, 1982; Dawkins, 1982; Dennett, 1995; Ridley, 1996). The MicroAnts simulation was one of the few programs reviewed that made explicit and primary use of genes as the focus for how agents in the system behaved. In the simulation, "ants" (coloured dots that can move about on the screen) have a 16-bit binary string which forms a single ant "chromosome" with nine "genes". This virtual genome influences how an ant will move, if it can detect poison, how it will interact with other ants (e.g., how and when it will fight and share food), and whether it can avoid being eaten by a virtual anteater (see "Gene scheme", Appendix E).

Third, the program makes use of genetic algorithms which are mathematical models of those processes operating in real biological systems. Thus, the simulation employs concepts related to basic genetics such as random mutation and cross-over. This adds to the program's authenticity as a computer model of evolutionary processes.
Fourth, the program makes data collection regarding the current state of the population of ants a very explicit and distinct part of using the simulation. That is, the simulation can be paused at any time during its execution and all of the environmental variables, including the genetic makeup of all ants currently alive, can be examined and saved for later analysis. This allowed for a detailed quantitative exploration of how individual ants and their genes behaved during the simulation. It is this quantitative examination of what transpired in the simulation that formed the focal point for the group dialogues during phases two and four of the current study. Last, the program was easy to install on any PC based computer and its interface was very simple to use. This was important because no prior knowledge of computers was assumed on the part of the participants.

Procedure

General. The class that was approached to participate in the study met as a group twice weekly as part of their Bachelor of Education programme. These meetings were used as an opportunity to complete and collect surveys, arrange and schedule computer sessions, and to discuss any questions or problems participants were having regarding the study. Before agreeing to take part in the investigation, participants were asked to read and sign a letter of informed consent (Appendix F). All participants who completed the study were paid 55 dollars, were given copies of all curriculum resources used and lesson plans produced in the investigation, were provided with a copy of all related computer software and were given a debriefing information sheet (Appendix G).

Phase 1 - Administer Questionnaires, Form dyads/triads. The purpose of phase one was to administer the paper and pencil surveys in order to: 1) examine participants' knowledge of evolutionary concepts (EKS), 2) obtain their perspectives regarding science epistemology (NOSS), and 3) assess their intentions to teach evolutionary concepts with their students (ITEQ). Of the three questionnaires, the NOSS was administered first in order to provide participants with a non-threatening introduction to the study. For the remaining two surveys, it was expected that administering the EKS before the ITEQ would result in a more accurate assessment of their true intentions to teach lessons on evolution. The rationale for this assumption was that students who enter a Bachelor of Education program tend to be very enthusiastic about teaching. By administering the EKS before the ITEQ, it was expected that participants would be more realistic in their evaluations of their intentions to teach evolution if they were able to reflect on their level
of understanding of evolutionary concepts as assessed by the EKS. Thus, while a counterbalanced administration of both surveys was considered, it was not implemented because it was assumed that the small number of participants would have precluded any instructive generalizations about order effects related to the administration of the questionnaires.

The NOSS was handed out to participants during a regular class meeting. They were instructed to complete the survey on their own time and to return it at their next class. One week later, at the next class meeting, all 22 NOSS surveys were collected from participants. Then, during this same class, participants were given 35 minutes to complete the EKS. Upon completion of the EKS, they were given the ITEQ questionnaire and were asked to complete it on their own time and to bring it with them to their next class. At the end of phase one, two participants indicated that they no longer wished to participate in the study and withdrew, citing lack of time as the reason for leaving.

Prior to the subjects' introduction to the simulations, the EKS was scored for the 20 remaining participants. A participant's EKS score was calculated and then categorized as being in the bottom (B), middle (M), or upper (U) third of the distribution of EKS scores for all participants. This resulted in classifying seven participants as having scores in the bottom of the distribution, seven as having scores in the middle of the distribution and six participants as having scores in the upper portion of the distribution. Before the next meeting of the class, a participant indicated that she had to leave the study due to illness. This participant's withdrawal from the study was unfortunate because she was the only one to receive a perfect score on the EKS. The 19 remaining subjects were grouped into three triads and five dyads for a total of eight groups.

An effort was made to compose the dyads and triads with participants from each of the three EKS categories (bottom, middle, upper). However, due to the small number of participants and the variability and overlap in their EKS scores, groups composed of one member from each of the three EKS categories was not possible. Thus, two triads were composed of one person with a bottom EKS score, one person with a middle EKS score, and one person with an upper EKS score (BMU). The other triad was composed of two participants with a bottom EKS scores, and one person with an upper EKS score (BBU). Two of the five dyads were composed of one person with a bottom EKS score, and one person with an upper EKS score (BU). Another two of the five dyads were
composed of participants who both had middle (though not identical) EKS scores (MM). The remaining dyad was composed of a participant with a bottom, and a participant with a middle EKS score (BM). These five dyads and three triads formed the bases for all group activities (i.e., simulation discussions and lesson planning) conducted during the remaining phases of the investigation.

**Phase 2 - Simulation for Familiarization.** The purpose of phase two was to familiarize participants with the simulation and to make them feel comfortable working in their groups while being audio taped. The purpose of using the simulation was to explore participants' knowledge of and discussion about evolutionary concepts in an applied setting. All eight groups met in one of the computer labs at the university. As participants entered the lab they were handed a copy of the MicroAnts manual (Appendix E) and were directed to sit in their groups at a computer that had the simulation installed on it.

Participants were then given a 20 minute introduction to the simulation by the author. The introduction involved going through each section of the MicroAnts manual to discuss: 1) the purpose of the simulation, 2) how to set up the environmental parameters, 3) how to run the simulation, 4) how to interpret the gene scheme, and 5) the general nature of the questions and how they were to be discussed. Any questions that participants had were answered during the introduction. Next, participants were instructed to start the simulation, turn on their tape recorders, and to begin following the step by step instructions contained in their manuals. The author's role was to act as a "detached" observer. That is, questions regarding procedural aspects of how to run the simulation were addressed as they arose. However, substantive questions related to evolutionary concepts per se were left to each group to resolve on their own. Overall, participants' conversations were recorded for approximately one hour. This included discussions while participants were running the simulation and while they were answering the questions related to the data it produced. The audio taped discussions were later transcribed for analysis.

After participants had run the simulation according to the instructions in the manual, they were asked to generate graphs related to the data collected during the simulation. The graphs were produced automatically with the aid of a spreadsheet program designed for this purpose. A total of 11 graphs were produced, nine "gene" graphs, one graph illustrating the number of ants alive at each sampling time, and a graph
illustrating the ants' food levels at each sampling time. Figure 3 is an example of a gene graph generated by participants in answer to a question posed in this phase.

The questions (Appendix E) were designed to elicit group members' thoughts about basic evolutionary processes and terms about the events that occurred during the simulation. Each group was given approximately 40 to 45 minutes to discuss the questions in the MicroAnts manual. All group members were encouraged to participate equally and to try and arrive at some type of consensus about their answers before moving on to the next question.

**Figure 3**
An example of a “gene” graph used by participants when answering the questions in the manual. This gene graph illustrates the percentage of surviving Red and Black ants with different *Strength* genes for sampled times (See Appendix E for details about each gene).

Originally, the group discussions were going to be interpreted within the framework of a coding scheme devised by Berkowitz and Gibbs (1985). Their coding scheme was developed in the context of examining the kinds of reasoning dyads used when discussing complex moral issues. Unfortunately, the nature of the interactions among dyads in this investigation did not lend itself to such an analysis. In short, while there were some good exchanges of ideas as participants answered questions, there was insufficient “give and take” dialogue (typical of the moral issues dialogues) among discussants to warrant the use of Berkowitz and Gibb's coding scheme in this study.
Instead, all the dialogues were examined for common themes into which participants' discussions could be categorized. Note, that because phase two was used to familiarize participants with the simulation, there was a great deal of variability in how much the members of the eight groups were able to accomplish. Thus, not all participants were able to answer all of the questions found in Appendix E for this phase of the investigation. Consequently, only two aspects of participants' dialogues were analyzed: 1) the exchanges among participants as they ran the simulation, and, 2) the discussions that took place as they answered the question pertaining to the “unit of selection” (Table 8).

Table 8
The dialogue and question used in the analysis of group discussions in phase two of the study.

<table>
<thead>
<tr>
<th>Simulation Activity / Question Examined for Analysis</th>
<th>Question Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Execution of the simulation.</td>
<td>How do participants view the objects and activities taking place on the screen as the simulation executes?</td>
</tr>
<tr>
<td>2) Is selection a phenomenon that happens to genes, to individuals, to populations or to species? Please explain the reasons for your answer. Feel free to make reference to the graphs on the “Data Summary” spreadsheet to support the reasons for your answer.</td>
<td>How do participants interpret the term &quot;selection&quot;?</td>
</tr>
</tbody>
</table>

Where definitive response categories emerged, prototypical responses were described and reproduced. A quantitative description that noted the number of groups that fell within these categories was also reported. Because of an equipment failure (a microphone failed to operate on one of the group's recorders), only seven of the eight dialogues from this phase of the study were available for analysis.

Phase 3 - Lesson Plan. The purpose of this phase of the investigation was to provide participants with quality resources related to evolution and then have them create a lesson plan on the process of natural selection. This phase of the study was implemented with the idea that it should mirror, at least in principle, the kind of activity that practicing teachers engage in when they are required to teach a lesson. In other words, this phase of the study was used as a method for exploring the extent to which a fundamental tenet of evolutionary biology (i.e., natural selection) could be learned by participants who indicated a weak understanding of the principle as it was assessed on the
EKS. Specifically, could participants who did not have a good understanding or who had misconceptions of basic evolutionary processes, learn them by simply engaging in the usual lesson planning activities typical of the teaching profession?

The dyads and triads were asked to create a 70 minute lesson plan dealing only with the concept of natural selection. The content of the lesson was to be suitable for students enrolled in a grade 11 or 12 high school biology course. The lesson plan on natural selection was incorporated into this investigation because creating a lesson plan was part of the regular work the class was required to do as part of their Bachelor of Education programme. All participants agreed to the nature of the assignment, were aware that their lesson plans would be graded and knew that all members of their group would receive the same grade.

The details and expectations for the lesson plan assignment were given to each student before the start of phase three (i.e., before they went out on their practice teaching assignments for six weeks). Participants were given an additional two weeks after they returned from practice teaching before having to turn in their lesson plans for grading. Thus, the groups had a total of approximately eight weeks to prepare their lessons. The location and type (e.g., science, math) of participants' practice teaching assignments were not known in advance. Thus, even if participants had been able to complete their lesson plans before finishing their practice teaching, it was unlikely that they could have had the opportunity to use it at the school where they were placed.

In addition, before leaving the university for their practice teaching assignments, all participants received the following curriculum resources: 1) "Teaching about Evolution and the Nature of Science" (National Academy of Sciences, 1998), 2) "Investigating Evolutionary Biology in the Laboratory" (McComas, 1994, chapters 1 and 7), 3) "Darwin's Dangerous Idea" (Dennett, 1995, pp. 39-60), and 4) access to a web-based resource created for this investigation (Macdonald, 1999, http://www.oise.utoronto.ca/~rmacdonald/evolution). These resources contain current information and activities related to natural selection and participants were encouraged to use these and any other resources they could find while out on practice teaching to help them create their lessons.

Phase 4 - Simulation for Exploration. The purpose of this phase of the study was to use the MicroAnts simulation in order to explore the participants' knowledge of evolutionary concepts in more depth. The general procedures for this phase of the study
were identical to those used in phase two. However, because participants were now familiar with the simulation and its overall operation, the introduction in this phase took only about 10 minutes to complete. Again, any questions participants had pertaining to how to run the simulation were addressed before they began using the program. Then, participants were asked to use their manuals (Appendix E) as before and to begin the simulation and follow the steps outlined in it.

The purpose of the questions used in this phase was the same as in phase two; to elicit group members' thoughts about basic evolutionary processes and terms as they related to the events that occurred while watching the simulation and to the data that were collected during the simulation. However, some changes in the questions used in this phase were implemented, for the following reasons (Appendix E). First, in phase two it was found that only one group was able to answer all eight questions in the time allotted. The reasons for this difference were due primarily to variability in the amount of time each group spent answering a given question and to variability in how quickly participants moved through the steps required to execute the simulation. Consequently, the number of questions was reduced from eight in phase two to six plus an extra question in phase four. This change, coupled with the shortened introduction, was effective in having the groups finish most of the questions.

Second, some groups indicated that they found the wording and intent of some of the questions in phase two unclear. In order to eliminate these ambiguities, all questions from phase two were reexamined. Thus, some questions were eliminated and those questions which were considered important in terms of their significance to the study's goals were reworded to make their intent as clear as possible for this phase. Last, in order to prevent participants from focusing on irrelevant parts of the questions, important aspects of the questions were emphasized in order to highlight their significance (see Appendix E). This change appeared to have the desired effect of keeping participants' attention focused on the significant details of a question.

Overall, all but one group were able to complete the seven questions. There were no equipment failures during this phase. Thus, the dialogues from all eight groups was available for analysis and the first six questions were examined for emerging themes. Table 9 lists the six questions that were used to promote group discussions during this phase of the investigation.
Table 9
The questions used in phase four of the study to promote group discussions.

<table>
<thead>
<tr>
<th>Questions Asked during Phase Four</th>
<th>Question Intent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Your computer has just randomly generated 200 virtual ants. Each of the other groups is using the same program and has entered the same environmental parameters. Will your group's description of how the population of ants changes over time be similar or unique compared to other groups? Please explain the reasons for your answer.</td>
<td>Does randomness have any role in the evolution of traits in a population?</td>
</tr>
<tr>
<td>2) Part A - For time 0 only, explain why you think the percentage of any of these 4 types of moving genes in the population (red or black ants) is roughly equal. You may want to look at 1 or 2 other graphs to confirm the pattern that at time 0 only, the percentage of ants that are expressing different types of that gene are roughly equal. You need to explain why this pattern exists. Part B - Do you think your answer for part 'A' above has any influence on what happens to the ants as they interact in this ecosystem? Please explain your answer.</td>
<td>Part A - Can participants explain the basic effects of randomness on a populations' evolution? Part B - How does randomness affect the evolution of traits in a population?</td>
</tr>
<tr>
<td>3) This question refers to the &quot;Poison-avoidance Genes&quot; graphs (# 5, alive or dead graphs). Do you think that these graphs indicate that there is a need among the red and black ants to avoid poison? Please explain your answer.</td>
<td>How do participants interpret the word &quot;need&quot;?</td>
</tr>
<tr>
<td>4) What is the difference between saying an ant is adapting (using &quot;adapt&quot; as a verb) to its environment versus saying an ant has an adaptation (using &quot;adapt&quot; as a noun) for its environment? Remember, please make reference to only one (1) of the gene graphs for your answer.</td>
<td>How do participants interpret &quot;adapting&quot; and &quot;adapting&quot;?</td>
</tr>
<tr>
<td>5) When answering this question please try to refer to one or two of the gene graphs. In this simulation, do you think anything resembling &quot;evolution by natural selection&quot; occurred with the population of red and black ants? Please explain the reasons for your answer.</td>
<td>How do participants interpret the principle of &quot;natural selection&quot;?</td>
</tr>
<tr>
<td>6) Part A - When answering this question please try to refer to one or two of the gene graphs. What does &quot;survival of the fittest&quot; mean? Please explain your answer. Part B - When answering this question please try to refer to one or two of the gene graphs. Could an ant be weak (strength = 1), cowardly (attacks = 0 - never) and lazy (movement = 0) and still be fit? Please explain your answer.</td>
<td>Part A - How do participants interpret the word &quot;fitness&quot;? Part B - How do participants apply the meaning given in part A?</td>
</tr>
</tbody>
</table>

As in phase two, after all steps for running the simulation were completed and graphs of the data had been generated, each group was given approximately 40 to 45 minutes to discuss the questions in the MicroAnts manual. All group members were encouraged to participate equally and to try and arrive at some type of consensus about their answers before moving on to the next question. The discussions were audio taped and later transcribed for analysis. Details of how the group dialogues for this phase were coded for analysis were similar to those used in phase two.
Phase 5 - Concept Map. The purpose of this phase of the study was to have participants complete concept maps to assess how they were able to interrelate major components of evolutionary theory (Trowbridge & Wandersee, 1994). The concept maps (Appendix H) were used to: 1) examine how participants' understanding of evolutionary principles were related to their conceptions of evolutionary theory as a whole, and 2) to explore possible relationships between participants' concept maps and their scores on the EKS. As Trowbridge and Wandersee (1994) noted, students require practice in completing concept maps before they can be utilized as a tool for learning and assessment. As part of their Bachelor of Education program, participants had already received some instruction in how to complete concept maps and had the opportunity to practice creating them.

During one of their regular class meetings, participants were provided with a sheet which contained instructions for how to complete the concept map, an example concept map and a sheet on which to draw their maps (Appendix H). They were given approximately 20 minutes to complete the task after being provided a brief (about five minutes) introduction to the task by the author. Participants were asked to draw a concept map that included the five “seed” concepts (genes, population, environment, mutation, natural selection), and to add at least four additional concepts. Also, participants were asked to associate their concepts by using descriptive linking words and phrases that indicated how all nine concepts were interrelated. Any questions that participants had about the task were answered before they began.

Originally, a rubric for scoring concept maps was developed in order to provide a standardized means of assessing each map (Trowbridge & Wandersee, 1994). However, the variability in participants' concept maps precluded using this scheme. Instead, the author and an independent expert examined the maps for any emerging themes. The first common theme that was apparent in the maps was related to misconceptions. Four categories of misconceptions were found in the maps: 1) Saltation, 2) Lamarckian, 3) Causal order, and 4) Level of selection. The other theme that emerged from the analysis of concept maps was related to a theme labelled “conceptually vague”. A concept map was placed in this category if it contained insufficient detail regarding how the concepts on the map were related. For all of the concept maps, there was 79% (n = 15) agreement between the researcher and the independent examiner on how a particular map should categorized. For the remaining 21% (n = 4) of the concept maps, the author and the
independent examiner discussed how each of these maps could be categorized until 100% agreement was attained.

**Phase 6 - Final Interviews.** The final interviews were conducted for the following purposes: 1) to assess participants' understanding of evolutionary concepts using applied problems, 2) to get personal perspectives on the usefulness of the simulation, and 3) to solicit participants' thoughts on the investigation as a whole. The final audio taped interviews took approximately 15 minutes to complete and were conducted in a face-to-face format with the researcher. At the end of the interview participants were given a debriefing information sheet (Appendix G), and were thanked for their participation in the study.

Participants were asked two applied questions in the final interview (Appendix I). These questions were identical to questions 13 and 14 on the EKS (Appendix A) that participants completed at the start of the study. Participants' responses to these two applied questions were transcribed from the audio tapes and given to an independent examiner who was instructed to score each answer as Darwinian, Lamarckian, or Other (Zusovksy, 1994). Inter-rater agreement between the author and the examiner on the first question (i.e., the Cheetah question) of the final interview was good (95%). Inter-rater agreement on the second question of the final interview (i.e., the Salamander question) of the final interview was also good (95%). Participants' responses regarding their perceptions of the usefulness of the simulation in helping them to learn evolutionary concepts and their responses regarding their perspectives on the investigation as a whole will be discussed in detail in the results section.
Chapter 4

Results: Questionnaire Data

One is not scientifically literate if one does not understand evolution
(Scott, 1996, p. 517).

Overview

This chapter will examine the data produced from the three questionnaires administered to the participants during phase one (see Table 6, p. 51) of the investigation. The three questionnaires were the Evolution Knowledge Survey (EKS, Appendix A), the Nature of Science Survey (NOSS, Appendix B) and the Intentions to Teach Evolution Questionnaire (ITEQ, Appendix C).

Knowledge of Evolution

Participants' knowledge of evolutionary concepts was assessed using the Evolution Knowledge Survey (EKS, see Appendix A). As noted in the previous chapter, only one participant received a perfect EKS score of 20. Unfortunately, this individual withdrew from the study due to illness. For the remaining 19 participants, the mean EKS score was 8.5 (sd = 3.9) and ranged from two to 15. Overall, 12 of the 19 participants (63%) scored less than 10 out of 20 on the EKS. The remaining seven participants (37%) scored between 10 and 15 out of 20. A breakdown of how participants performed on each of the 20 EKS questions is indicated in Table 10. The table has been organized according to the percentage of participants who correctly answered each of the 20 EKS items, from highest percentage correct to lowest percentage correct. Generally, Table 10 reveals that eight of the 20 items (3, 9, 10, 16d, 16e, 16f, 16i, 16j) were answered correctly by more than half of the participants while the remaining 12 items (1, 2, 4, 5, 6, 7, 8, 12, 16a, 16b, 16c, 16g, 16h) were answered correctly by less than half the participants.

Overall, these results provide an answer to the first research question. That is, in this sample of Ontario Intermediate/Senior pre-service science teachers 12 of the 19 participants (63%) were unable to pass (i.e., 10/20) a test designed to assess one's understanding of basic evolutionary concepts. Of the seven participants (37%) who did pass the test, only two (11%) could be considered to have a good understanding of basic evolutionary concepts (EKS = 15). Thus, these results are highly consistent with findings
reported in the literature for similar samples of subjects in other countries (e.g., Brumby, 1984; Zuzovskv, 1994).

Table 10
Percentage of participants who answered each of the 20 EKS questions correctly arranged from highest percentage correct to lowest percentage correct.

<table>
<thead>
<tr>
<th>EKS Item</th>
<th>Percentage Correct (n = 19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16e</td>
<td>79</td>
</tr>
<tr>
<td>16j</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
</tr>
<tr>
<td>9</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>63</td>
</tr>
<tr>
<td>16d</td>
<td>58</td>
</tr>
<tr>
<td>16f</td>
<td>53</td>
</tr>
<tr>
<td>16i</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>42</td>
</tr>
<tr>
<td>16a</td>
<td>42</td>
</tr>
<tr>
<td>7</td>
<td>37</td>
</tr>
<tr>
<td>8</td>
<td>37</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
</tr>
<tr>
<td>16c</td>
<td>26</td>
</tr>
<tr>
<td>16h</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>16g</td>
<td>11</td>
</tr>
<tr>
<td>16b</td>
<td>05</td>
</tr>
</tbody>
</table>

However, these findings must be qualified by noting that there was a difference among participants who passed and failed the EKS regarding the number of reported full-time biology courses taken during their undergraduate education. Specifically, the mean number of full-time biology courses reported by those who failed the EKS was 3.8 (sd = 2.1). On the other hand, the mean number of full-time biology courses taken by those who passed the EKS was 4.6 (sd = 3.2). Overall, the mean number of reported full-time undergraduate biology courses taken ranged from 0 to 9. Surprisingly, both groups (i.e., those who passed and those who failed the EKS) had one individual who reported taking no undergraduate biology courses.

In order to estimate the strength of the association between the number of full-time undergraduate biology courses taken and participants' score on the EKS, a Pearson
correlation was performed and was found to be weak \((r = .21)\). Thus, generally, there was some association between the number of full-time biology courses taken and participants' EKS score. However, the overall influence of undergraduate biology courses on participants' level of evolutionary knowledge was, at best, weak.

**Intentions to Teach Evolution**

Participants' intentions to teach evolution by natural selection were assessed using a paper and pencil survey, the Intentions to Teach Evolution Questionnaire (ITEQ, see Appendix C). As outlined earlier, the construction of the scale's items was based on the Theory of Planned Behaviour (Ajzen, 1985). The Theory of Planned Behaviour posits that an individual's *intentions* are the best predictor of what an individual will actually *do* (see Figure 1, p. 28).

Recall that an individual's intention score is calculated in the following manner.

\[
I = W_1 \left[ \sum_{i=1}^{N} b_i * e_i \right] + W_2 \left[ \sum_{i=1}^{N} nb ^ * mc \right] + W_3 \left[ \sum_{i=1}^{P} cb ^ * lo \right]
\]

Five of the six sub-scales (i.e., b, nb, mc, cb, lo) are composed of items that are anchored at -3 by "extremely unlikely" and at +3 by "extremely likely". Participants use a 7-point Likert scale to rate the likelihood that the event described by an item would occur. The other sub-scale, (e), is composed of items that are anchored at -3 by such terms as "extremely bad", "extremely useless", "extremely harmful" and at +3 by such terms as "extremely good", "extremely useful", "extremely beneficial". Participants use this 7-point Likert scale to rate their evaluation of the consequences of that event if it were to occur. For example, a participant might believe (b) that it was "slightly likely" \((b = +1)\) that teaching evolution by natural selection "could offend some students". Also, this participant might evaluate (e) this outcome as "slightly bad" \((e = -1)\). According to Ajzen (1985), this individual's attitude \((b \times e)\) towards teaching evolution by natural selection for this item is slightly negative \((-1)\).

Overall, a participant's score could range from -9 to +9 for any one item that comprises the three major sub-scales. The individual item scores are then summed for each of the major sub-scales, attitude (A), subjective norm (SN), and perceived behavioural control (PBC), according to the formula noted above. To compare the relative influence of each sub-scale, a mean score for each of A, SN, PBC is obtained by
dividing the total sub-scale score by the number of questions that comprised the sub-scale. In this investigation, the 'A' sub-scale was composed of 42 (2 x 21) items, the SN sub-scale was composed of 14 (2 x 7) items, and the PBC scale was composed of 14 (2 x 7) items. The result, when all the elements of the equation are combined, is an intention (I) score. The higher the intention score, the more likely it is that a person will engage in the given behaviour. Different weights can be applied to each factor depending on the number of questions used in each of the sub-scales or on contextual variables that might alter the relative influence of each element. Theoretically, ITEQ scores can range from a minimum of -27 to a maximum of +27 (the sum of the mean values for A, SN, and PBC).

The mean ITEQ score for all 19 participants was 8.5 (sd = 3.6). Participants' ITEQ scores ranged from 1.7 to 11.2. Because none of the literature reviewed for this investigation examined participants' intentions to teach evolution in the classroom, these values cannot be placed in a broader context. To explore the effects of low and high ITEQ scores with other variables, a median split of the ITEQ scores was performed. The median ITEQ score was 7.8. Participants who had an total ITEQ score of 7.8 or below (n = 10) were categorized as belonging to the “low” intention group. Participants who had an total ITEQ score greater than 7.8 (n = 9) were categorized as belonging to the “high” intention group. The mean ITEQ score for participants in the low intention group was 5.7 (sd = 2.0) while the mean ITEQ score for participants in the high intention group was 10.8 (sd = 2.9).

Table 11 shows the means and standard deviations for each of the three intention subscales for the low and high intention groups. Table 11 reveals two noteworthy findings. First, for all three intention components, the mean scores for the low intention group were lower than the mean scores for the high intention group. That is, the low intention group had lower attitude (A), subjective norm (SN), and perceived behavioural control (PBC) scores when compared to the high intention group. Second, the relatively low PBC scores for both groups indicate that participants, as a whole, believe that teaching evolution by natural selection is complicated by internal (e.g., inadequate information, skill, ability) and by external factors (e.g., lack of resources, time). Specific details of how the high and low intentions groups varied as a function of these particular ITEQ component items are discussed below in the subsection on the interrelationship between knowledge and intentions.
Table 11
Mean and standard deviations of Intention component scores for participants in the low and high intention groups.

<table>
<thead>
<tr>
<th>Intention Category</th>
<th>Intention Subscale</th>
<th>Low (n = 10)</th>
<th>High (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Attitude (b x e)</td>
<td>2.7 (1.1)</td>
<td>4.4 (1.6)</td>
</tr>
<tr>
<td></td>
<td>Subjective Norm (nb x mc)</td>
<td>1.9 (1.3)</td>
<td>3.9 (2.1)</td>
</tr>
<tr>
<td></td>
<td>Perceived Behavioural Control (cb x lo)</td>
<td>1.1 (1.2)</td>
<td>2.5 (1.5)</td>
</tr>
</tbody>
</table>

Note: Standard deviations appear in parentheses.

Perspectives on the Nature of Science
Participants’ perspectives on the nature of science were explored using the Nature of Science Survey (NOSS, see Appendix B). The NOSS is composed of two parts. Part A of the NOSS (i.e., the VOSTS) was designed exclusively as a qualitative instrument. The approach typically employed for reporting the results from the VOSTS, and the one that will be used here, is to list each question and report the percentage of individuals who endorsed a particular response to each item (Aikenhead & Ryan, 1992). Table 12 lists all the VOSTS questions from the NOSS and the percentage of participants who responded to a particular item for that question. The table is arranged by decreasing degree of “collective opinion” for a given question. Collective opinion is used here to connote the item endorsed by the greatest percentage of participants. There is also another sense in which this arrangement of VOSTS items reflects some degree of consensus among participants. All 19 participants’ perspectives are captured by four or fewer VOSTS items on the six questions (12, 1, 9, 8, 15, 4). In contrast, questions (19, 2, 10, 6, 16, 20, 11, 17, 3) required five or more VOSTS items to capture all 19 participants’ perspectives. The middle five items (13, 18, 5, 14, 7) are a mix of degrees of consensus.

Botton and Brown (1998) suggested several semantic categories or conceptual schemes that could be used to classify these 20 VOSTS questions (see Table 13 for their epistemological categories). Unfortunately, the small number of items in each category and the relatively small number of study participants makes it difficult to generate any substantive conclusions. Nonetheless, there are some general observations worth noting. As shown in Table 12, the greatest consensus among participants’ perspectives appears to be in the area categorized by Botton and Brown as “scientific approach to investigations” (i.e., category 06, questions 12, 8, 9). Specifically, the majority of participants
Table 12
Percentage of participants (n = 19) who responded to each item for a given VOSTS question.

| VOSTS Question | VOSTS Item Endorsed | A | B | C | D | E | F | G | H | I | J | K | L |
|----------------|---------------------|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12 (06)        |                     | 5.3 | 0.0 | 5.3 | 5.3 | 5.3 | 0.0 | 0.0 | - | - | - | - | - | - |
| 1 (01)         |                     | 15.8 | 15.8 | 0.0 | 5.3 | 0.0 | 0.0 | - | - | - | - | - | - | - |
| 8 (06)         |                     | 0.0 | 0.0 | 0.0 | 0.0 | 26.3 | 0.0 | 10.5 | 0.0 | 0.0 | 0.0 | 0.0 | - | - |
| 9 (06)         |                     | 26.3 | 0.0 | 5.3 | 5.3 | 0.0 | 0.0 | - | - | - | - | - | - | - |
| 15 (08)        |                     | 0.0 | 21.1 | 5.3 | 5.3 | 0.0 | 0.0 | 10.5 | 0.0 | - | - | - | - | - |
| 4 (04)         |                     | 31.6 | 5.3 | 10.5 | 0.0 | 0.0 | 0.0 | - | - | - | - | - | - | - |
| 13 (07)        |                     | 5.3 | 15.8 | 5.3 | 15.8 | 0.0 | 0.0 | - | - | - | - | - | - | - |
| 18 (10)        |                     | 10.5 | 0.0 | 0.0 | 5.3 | 5.7 | 21.1 | 5.3 | 0.0 | - | - | - | - | - |
| 5 (05)         |                     | 0.0 | 0.0 | 0.0 | 5.3 | 36.8 | 10.5 | 0.0 | 0.0 | - | - | - | - | - |
| 14 (07)        |                     | 36.8 | 5.3 | 5.3 | 0.0 | 0.0 | - | - | - | - | - | - | - | - |
| 7 (05)         |                     | 10.5 | 15.8 | 26.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - |
| 19 (10)        |                     | 10.5 | 21.1 | 10.5 | 5.3 | 5.3 | 0.0 | - | - | - | - | - | - | - |
| 2 (02)         |                     | 0.0 | 5.3 | 0.0 | 5.3 | 26.3 | 10.5 | 10.5 | 0.0 | 5.3 | - | - | - | - |
| 10 (06)        |                     | 0.0 | 5.3 | 36.8 | 5.3 | 5.3 | 0.0 | 0.0 | 5.3 | - | - | - | - | - |
| 6 (05)         |                     | 10.5 | 26.3 | 21.1 | 0.0 | 0.0 | 0.0 | 36.8 | 5.3 | - | - | - | - | - |
| 16 (09)        |                     | 31.6 | 0.0 | 15.8 | 5.3 | 5.3 | 0.0 | 10.5 | - | - | - | - | - | - |
| 20 (11)        |                     | 26.3 | 26.3 | 5.3 | 5.3 | 5.3 | 0.0 | 0.0 | - | - | - | - | - | - |
| 11 (06)        |                     | 26.3 | 0.0 | 5.3 | 26.3 | 21.1 | 5.3 | 5.3 | 0.0 | 0.0 | - | - | - | - |
| 17 (10)        |                     | 26.3 | 5.3 | 15.8 | 5.3 | 21.1 | 0.0 | 0.0 | - | - | - | - | - | - |
| 3 (03)         |                     | 0.0 | 5.3 | 5.3 | 26.3 | 10.5 | 0.0 | 5.3 | - | - | - | - | - | - |

Note: Botton and Brown epistemological categories are in parentheses.

Table 13
Epistemological categories for each of the 20 VOSTS items (adapted from Botton & Brown, 1998).

<table>
<thead>
<tr>
<th>Classification Code</th>
<th>VOSTS item(s)</th>
<th>Science Epistemology Category: Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>1</td>
<td>Nature of observations (e.g., theory ladenness, perception bound)</td>
</tr>
<tr>
<td>02</td>
<td>2</td>
<td>Nature of scientific models</td>
</tr>
<tr>
<td>03</td>
<td>3</td>
<td>Nature of classification schemes</td>
</tr>
<tr>
<td>04</td>
<td>4</td>
<td>Tentativeness of scientific knowledge</td>
</tr>
<tr>
<td>05</td>
<td>5, 6, 7</td>
<td>Hypothesis, theories &amp; laws (e.g., definition, role of assumptions, criteria for belief)</td>
</tr>
<tr>
<td>06</td>
<td>8, 9, 10, 11, 12</td>
<td>Scientific approach to investigations (e.g., nonlinearity, rejection of a stepwise procedure, &quot;the scientific method&quot; as a writing style)</td>
</tr>
<tr>
<td>07</td>
<td>13, 14</td>
<td>Precision and uncertainty in scientific/technological knowledge (e.g., probabilistic reasoning)</td>
</tr>
<tr>
<td>08</td>
<td>15</td>
<td>Logical reasoning (e.g., cause/effect problems, Epidemiology &amp; etiology)</td>
</tr>
<tr>
<td>09</td>
<td>16</td>
<td>Fundamental assumptions for all science (e.g., uniformitarianism)</td>
</tr>
<tr>
<td>10</td>
<td>17, 18, 19</td>
<td>Epistemological status of scientific knowledge (e.g., ontology as an assumption, questioning logical positivism)</td>
</tr>
<tr>
<td>11</td>
<td>20</td>
<td>Paradigms vs. coherence of concepts across disciplines</td>
</tr>
</tbody>
</table>
(≥ 63%) indicated that they believed: 1) errors are an inherent (and even welcomed) part of science (12d), 2) that following the scientific method means questioning, hypothesizing, collecting data and concluding (8g), and 3) that the scientific method, while useful, does not guarantee results; originality and creativity are also needed (9c).

In comparison, the last nine VOSTS questions, as categorized in Table 13, cover a broad range of epistemological categories and participants' responses are remarkable for their heterogeneity. That is, for participants, there is very little consensus on a broad spectrum of questions related to the nature of scientific knowledge. Particularly diverse were participants' responses to questions that dealt with Botton and Brown's (1998) category of "epistemological status of scientific knowledge" (i.e., questions 17, 18, 19). For example, 31.6% of the participants responded with a "positivist" perspective with respect to scientific laws (e.g., "laws are based on experimental facts", 17b) but appeared to adopt a more "relativist" perspective with regard to scientific hypotheses (e.g., "a hypothesis is an interpretation of experimental facts which scientists have discovered", 18e).

Participants' responses to question 10 of the VOSTS, which Botton and Brown suggested deals with "scientific approach to investigations", deserves close examination. Specifically, for question 10, item 'c' was endorsed by 36.8% of the participants and item 'd' was endorsed by 42.1% of the participants for a total of almost 79% for these two items. Item 'c' is worded: "Usually scientific discoveries result from a logical series of investigations. But science is not completely logical. There is an element of trial and error, hit and miss, in the process" (original emphasis). Item 'd' is worded: "Some scientific discoveries are accidental, or they are the unpredicted product of the actual intention of the scientist. However, more discoveries result from a series of investigations building logically one upon the other" (original emphasis). If the two sentences in item 'd' were reversed, then the semantic content of both items specify relatively identical propositions (depending on the extent to which participants differentiated between "usually" and "more" and between "not completely" and "some". As such, if participants' responses for items 'c' and 'd' are combined, then there is a fair degree of quantitative and qualitative consensus for how they answered questions eight, nine, 10, and 12. In other words, the apparent disparity in how participants responded to question 10 is somewhat illusory. In general, most (≥ 63%) of the participants tended to agree on their perspectives which connote a "scientific approach to investigations."
Part B of the NOSS (Appendix B) is a questionnaire developed by Nott and Wellington (1993). The Nott and Wellington (NW) questionnaire produces a profile for each user on five dimensions (see Table 7, p. 56). The main purpose for including the NW scale in this study was to examine participants' scores on the PR (Positivist/Relativist) dimension. Recall that one research question of interest predicted that individuals who endorsed a "positivist" view of science would have higher scores on a test of evolutionary knowledge when compared to participants who endorsed a more "relativist" view of science.

The mean, standard deviations and range of scores for the five dimensions of the NW scale for are presented in Table 14. Each of Nott and Wellington's (1993) dimensions have scores that can vary over a wide range of values. For example, scores on the Positivist-Relativist (PR) dimension can range from -40 (Positivist) to +40 (Relativist). Scores on the Inductivist-Deductivist (ID) dimension can range from -20 (Inductivist) to +20 (Deductivist). Scores on the Decontextualist-Contextualist (DC) dimension can range from -40 (Decontextualist) to +40 (Contextualist). Scores on the Content-oriented-Process-oriented (CP) dimension can range from -25 (Content) to +25 (Process). Scores on the Realist-Instrumentalist (RI) dimension can range from -25 (Realist) to +25 (Instrumentalist).

Table 14 indicates a consistent tendency for participants to endorse perspectives that are oriented towards the middle of each dimension. Thus, participants were unlikely to advocate an extreme perspective for any one of the five dimensions. In fact, only three participants had dimension scores that exceeded the midpoint in the total range for any of the five dimensions. That is, only two subjects exhibited a moderate "Process" orientation (i.e., CP = 13) and only one subject endorsed a moderately "Relativist" orientation (i.e., PR = 22). In terms of the overall distribution of scores within a dimension, only the PR and CP scales revealed any large differences in response patterns. Sixty-eight percent of the participants endorsed a slightly "Relativist" oriented perspective (mean PR = 7.8, sd = 6.5) and 74% of the participants endorsed a slightly "Process" oriented perspective (mean CP = 6.8, sd = 4.5). The remaining dimensions, ID, DC, and RI had roughly equal percentages (52/42, 42/52, 42/52, respectively) of individuals who weakly endorsed one perspective or the other within the specified dimensions.
Table 14. Means, standard deviations and ranges for participant scores on the five dimensions of the Nott and Wellington (1993) "Nature of Science" scales.

<table>
<thead>
<tr>
<th>Nott and Wellington Dimensions on the Nature of Science</th>
<th>PR</th>
<th>ID</th>
<th>DC</th>
<th>CP</th>
<th>RI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (sd)</td>
<td>4.4 (7.7)</td>
<td>-1.7 (4.4)</td>
<td>0.79 (7.4)</td>
<td>4.2 (6.0)</td>
<td>1.4 (6.7)</td>
</tr>
<tr>
<td>Range</td>
<td>-8 to 22</td>
<td>-9 to 5</td>
<td>-15 to 12</td>
<td>-8 to 13</td>
<td>-11 to 12</td>
</tr>
</tbody>
</table>

Note: Standard deviations are in parentheses.

Overall, Part B of the NOSS revealed that the 19 participants in this study tended to endorse moderate, multidimensional perspectives on the nature of science as assessed by Nott and Wellington's (1993) scale. Results pertaining to how the high and low EKS groups varied as a function of specific questions in both parts A and B of the NOSS are discussed below in the subsection on the interrelationship between evolutionary knowledge and perspectives on the nature of science.

Knowledge and Intentions

For the purposes of examining how a participant's knowledge of evolutionary concepts was interrelated with their intentions to teach evolution, a median split of the EKS scores was performed. The median EKS score was eight. Therefore, participants who had an total EKS score of eight or below (n = 10) were categorized as belonging to the "low" evolutionary knowledge group. Participants who had an total EKS score greater than eight (n = 9) were placed into the "high" evolutionary knowledge group. The mean EKS score for participants in the low knowledge group was 5.6 (sd = 2.2) while the mean EKS score for participants in the high knowledge group was 12.1 (sd = 2.4).

Table 15 indicates the number of participants who fell within each of the four cells created as a function of the median splits for these two variables (i.e., low knowledge/low intention, low knowledge/high intention, high knowledge/high intention, high knowledge/high intention). This table reveals that eight of the 19 participants (42%) who had a low EKS score also exhibited a low ITEQ score (the LL group). Conversely, seven of the 19 participants (37%) who had a high EKS also exhibited a high ITEQ score (the HH group). Only four of the 19 participants (21%) were categorized as having mixed (i.e., LH or HL) EKS by ITEQ scores. Because the overall sample size in this study was relatively small, the number of participants categorized as "indifferents" (high knowledge, low intentions, n = 2) and "enthusiasts" (low knowledge, high intentions, n =
2) was too low to allow for any definitive conclusions. Subsequently, only results pertaining to the LL and HH groups will be discussed in detail.

Table 15
Number of participants categorized by knowledge of evolutionary concepts (low, high) and intentions to teach evolutionary concepts (low, high).

<table>
<thead>
<tr>
<th>Knowledge</th>
<th>Intentions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>8</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
</tr>
</tbody>
</table>

It appears from Table 15 that the second research question of interest in this study, "Can Intermediate/Senior pre-service science teachers' knowledge of evolutionary concepts aid in the prediction of their intentions to teach evolution by natural selection?", can be answered affirmatively. That is, for 15 of the 19 of participants (79%), their score on the EKS allowed for a reasonably accurate prediction of their ITEQ score. Specifically, those with relatively low EKS scores tended to have relatively lower intentions to teach evolution by natural selection. On the other hand, individuals with relatively high EKS scores also had relatively higher intentions to teach evolution by natural selection.

To understand more clearly how the LL and HH groups differed on each of the intention components, Table 16 presents the mean ITEQ scores for each of the three dimensions. In order to examine how the three components distinguished between the two groups, it is necessary to discuss the specific items that were used within each of the dimensions of the ITEQ. Therefore, a criterion by which an item in any one of the dimensions could be considered important was established. An arbitrary difference score of two was used as the criterion. That is, if the absolute mean difference value between the LL and HH group was two or greater, then that item was deemed important enough to warrant further discussion. Conversely, differences of less than two were interpreted as relatively minor distinctions between individuals in the LL and HH groups.

First, on the SN dimension, the HH group had higher mean scores on all seven items that comprised this dimension (Appendix C). However, only one of the seven items (14%) on this dimension had a mean difference score greater than two. The item regarding the influence of students' parents in their decision to teach evolution by natural
selection revealed the HH group's mean score (+4) exceeded the LL group's mean score (+1) by two or more. The mean subjective norm scores for other important referent groups (i.e., friends, religious organization, school board, principal, other teachers, students themselves) were relatively unimportant in distinguishing among the LL and HH group for this intention component. Overall, these results indicate that relative to the LL group, the HH group believe that students' parents could be an influential referent group that could affect their decisions to teach evolution by natural selection and, furthermore, that they are relatively willing to comply with this referent group. Note that this conclusion does not reveal the nature of how such influence might operate. The discussion below on the attitudinal component of the ITEQ appears to shed some light on the kinds of issues that may be related to the nature of this influence.

Table 16
Participants' mean scores and standard deviations for items on the three intention components as a function of their knowledge-intention category.

<table>
<thead>
<tr>
<th>Knowledge / Intention Category</th>
<th>Intention Component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Attitude (b x e) (21 items)</td>
</tr>
<tr>
<td>Low / Low (n = 8)</td>
<td>2.9 (1.2)</td>
</tr>
<tr>
<td>High / High (n = 7)</td>
<td>4.0 (1.5)</td>
</tr>
</tbody>
</table>

Note: Standard deviation are in parentheses.

On the PBC dimension, again, the HH group had higher mean scores on all seven items that comprised the dimension (Appendix C). Three of the seven items (43%) (relying on available text books, being pressed for time, and factors beyond my control) on this dimension had difference scores where the HH group was higher that the LL group by two or more (2.2, 2.3, 4.3, respectively). Whereas, items that expressed ideas about PBC over teaching evolution by natural selection (letting students decide, teaching the theory will be up to me, not having well developed curriculum materials, and personal background knowledge from university courses) did not differentiate among the groups by a mean value greater than two. Overall, these results suggest that relative to the HH group, the LL group believed that teaching evolution by natural selection would be complicated primarily by external factors (e.g., lack of time, having to rely on available texts, and factors beyond their control).
On the attitude dimension, there were several items that exceeded a mean difference score of two when compared to the LL and HH groups. These items are worth exploring in detail because very little literature could be found that addressed specific beliefs and attitudes as they relate to individuals' thoughts on teaching evolution by natural selection. Table 17 lists all 21 items that comprised the attitudinal dimension of the ITEQ scale. The first column lists the item, the next two columns contain the mean and standard deviation for the respective groups and the last column provides the difference score between the mean values found in columns two and three. Table 17 is arranged in ascending order of these difference scores. Recall that a positive attitude score suggests that a participant has a favourable attitude towards that item, and a negative value indicates a negative attitude.

The first thing to note about Table 17 is that, unlike the SN and PBC dimensions, there were three items where the HH group had mean scores for that item that were lower and two that were negative in direction when compared to the LL group. Although, only items 2 and 15 exceeded an absolute mean difference score of two or more. Importantly, these two items (2, 15) deal with affective-type outcomes. In other words, on average, compared to the LL group, the HH group reported negative attitudes towards the likelihood of “upsetting” and “offending” their students as a result of teaching the theory of evolution by natural selection. The second important point to note is that 15 of the 21 items (71%) that made up the attitude dimension resulted in a mean difference score between the LL and HH group that exceed the criterion value of two or more. In other words, the attitude dimension had a much larger percentage of items that differentiated between the LL and the HH group compared to the percentage of items that differentiated these groups on the SN (14%) and PBC (43%) sub-scales.

The items that are most noteworthy in Table 17 are those where the mean difference scores when comparing the two groups exceed a value of three (items 15, 17, 11, 13, 21, 20, 12). Interestingly, four of these items (17, 13, 21, 20) deal specifically with evolution as it pertains to humans, and two items deal specifically with the two most fundamental aspects of science epistemology: 1) the nature of scientific evidence, and 2) the means by which such evidence is evaluated: critical thinking. The other important point to note about Table 17 is that the overall range of attitude scores for the LL group (-0.3 to 5.1) is smaller and scores are all positive except for one item. Whereas, the range
of attitude scores for the HH (-2.3 to 7.9) group is larger and contains values that indicate a relatively strong negative attitude towards two items.

Table 17.
The means, standard deviations and difference scores for items that comprise the “Attitude” dimension of the ITEQ scale as a function of low intention/low knowledge (LL) group and the high knowledge/high intention (HH) group.

<table>
<thead>
<tr>
<th>ITEQ Attitude Item Regarding Intention Towards Teaching Evolution by Natural Selection</th>
<th>Mean Attitude (b x e) per Item</th>
<th>LL (sd)</th>
<th>HH (sd)</th>
<th>Diff. (HH - LL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15) could end up upsetting a lot of people.</td>
<td>1.6 (3.9)</td>
<td>-2.0 (4.1)</td>
<td>-3.6</td>
<td></td>
</tr>
<tr>
<td>02) could offend some of them.</td>
<td>0.0 (3.0)</td>
<td>-2.3 (2.4)</td>
<td>-2.3</td>
<td></td>
</tr>
<tr>
<td>04) could create a lot of controversy in the class.</td>
<td>0.8 (1.7)</td>
<td>0.4 (4.4)</td>
<td>-0.3</td>
<td></td>
</tr>
<tr>
<td>07) could be difficult for me because of my religious beliefs.</td>
<td>1.0 (3.3)</td>
<td>1.0 (3.6)</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>08) could end up confusing most of them.</td>
<td>1.8 (2.7)</td>
<td>2.3 (2.4)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>18) could lead to conflict in the science department at my school.</td>
<td>3.1 (3.8)</td>
<td>3.7 (3.2)</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>14) could help them to understand adaptations and how they can emerge in a population of organisms.</td>
<td>5.1 (2.1)</td>
<td>6.6 (1.8)</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>03) could help them appreciate why there is such a diversity of life forms on the planet.</td>
<td>5.1 (2.1)</td>
<td>6.7 (2.3)</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>06) could be a way to help them learn about important people and events in the history of science.</td>
<td>2.3 (2.0)</td>
<td>4.4 (3.3)</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>05) could be a way to show them how theories can be used in science.</td>
<td>3.5 (1.4)</td>
<td>5.7 (2.9)</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>19) could help them to understand why some species go extinct.</td>
<td>4.4 (2.3)</td>
<td>6.7 (2.3)</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>09) could help them learn about other aspects of Biology.</td>
<td>3.6 (1.5)</td>
<td>6.0 (2.2)</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>10) could help them learn about genetics.</td>
<td>3.3 (1.5)</td>
<td>5.7 (1.9)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>16) could provide a way to integrate many other subjects (e.g., Mathematics, Reading, English) into science lessons.</td>
<td>1.4 (3.6)</td>
<td>3.9 (3.4)</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>01) could help them to understand ideas about the nature of science.</td>
<td>3.5 (1.7)</td>
<td>6.1 (3.1)</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>17) could provide insight into human development.</td>
<td>2.1 (2.3)</td>
<td>5.1 (2.3)</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>11) could help promote critical thinking.</td>
<td>3.8 (2.3)</td>
<td>7.0 (2.0)</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>13) could help them to understand some of the reasons behind human behaviour.</td>
<td>2.0 (1.8)</td>
<td>5.7 (2.6)</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>21) could help them to understand human brain functioning and cognition.</td>
<td>-0.3 (2.4)</td>
<td>3.9 (3.4)</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>20) could help them understand why some antibiotics have become less effective against certain kinds of bacteria.</td>
<td>3.3 (4.0)</td>
<td>7.9 (2.0)</td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>12) could help them see how evidence is used in science.</td>
<td>2.1 (2.9)</td>
<td>7.4 (2.1)</td>
<td>5.3</td>
<td></td>
</tr>
</tbody>
</table>
Knowledge and Perspectives on the Nature of Science

The first part of this section will deal with the differences in perspective between the low knowledge (LK) and high knowledge (HK) groups obtained from Part A of the NOSS (Appendix B). The second part of this section will deal with the third research question which examined whether participants who endorsed a more positivist perspective on the nature of science would score higher on the EKS when compared to those who endorsed a more relativist perspective. Data to address this question were obtained from Part B of the NOSS (Appendix B).

Differences between the LK (n = 10) and HK (n = 9) groups on Part A (VOSTS, Akienhead & Ryan, 1992) of the NOSS revealed a great deal of overlap in perspectives between the two groups. To explore potentially meaningful differences between the two groups, a criterion was established for determining which of the response patterns were most disparate. Thus, if the groups differed by more than 33% on a question (i.e., about three or more respondents), then it was considered for further examination. Table 18 lists 4 out of the 20 VOSTS items that met this criterion.

Table 18
VOSTS questions where the LL and HH groups differed in number of respondents by more that 33%.

<table>
<thead>
<tr>
<th>VOSTS Question / Group</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 / LK</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 / HK</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 / LK</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 / HK</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 / LK</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 / HK</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 / LK</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 / HK</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The HK group had three more respondents to questions 3, 9, and 17 when compared to the LK group. The LK group had four more respondents to question one. All four questions address different epistemological categories of Botton and Brown's classification scheme for VOSTS items (see Table 13, p. 74). Table 18 also reveals that the overall pattern of responses for the other items within a question is very similar for both the LK and HK groups. Overall, only 4 of the 20 questions revealed any noteworthy differences in response patterns between the LK and HK groups. For those questions that
did show some disparity, the differences (in how LK and HK participants responded) were not exceptional in either number or in perspective.

With regard to this study's third question, Table 19 indicates the mean scores across all five dimensions of part B of the NOSS as a function of participants' EKS scores. The data revealed that those who endorsed a more relativist perspective on the nature of science tended to score higher on the EKS when compared to those who endorsed a less relativist perspective (see PR dimension, Table 19).

Table 19
Means and standard deviations for the five dimensions of the Nott and Wellington (1993) "Nature of Science" scales as a function of participants' scores on the EKS (high and low).

<table>
<thead>
<tr>
<th>Group</th>
<th>Nott and Wellington Dimensions on the Nature of Science</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PR</td>
</tr>
<tr>
<td>Low EKS (n = 10)</td>
<td>3.0 (7.8)</td>
</tr>
<tr>
<td>High EKS (n = 9)</td>
<td>5.9 (7.9)</td>
</tr>
</tbody>
</table>

Note: Standard deviations are in parentheses.

Overall, the table reveals very little difference between the two groups on any of the five dimensions; all means scores are within half of a standard deviation of each other. These data, coupled with the data from Part A of the VOSTS noted above, suggest that knowledge of evolutionary concepts, as assessed by the EKS, is relatively unrelated to participants' perspectives on the nature of science, as revealed by the NOSS.

Summary

In summary, this chapter examined the first two sub-goals and answered the study's first three research questions. Generally, for the large majority of participants, their knowledge of evolutionary concepts, as measured by the EKS, can be considered poor. These results support other findings from studies dealing with similar groups of subjects. An exploratory measure, the ITEQ, was used to assess participants' intentions to teach evolution by natural selection. This measure revealed that participants' attitudes towards teaching evolution by natural selection accounted for most of the variance in their overall ITEQ scores relative to the subjective norm and perceived behavioural
control components of the ITEQ. The attitude items that most differentiated high and low intention participants dealt with evolution as it pertains to humans.

Participants' perspectives on the nature of science, as defined by the NOSS, revealed a relatively heterogeneous view of science epistemology. Only perspectives regarding “scientific approaches to investigations” demonstrated any consistent consensus among participants. With regard to the interaction between participants' knowledge of evolutionary concepts and their intentions to teach evolution by natural selection, as assessed by the EKS and ITEQ, respectively, a reasonably strong association was found. That is, 79% of the participants' ITEQ scores (low vs. high) could be predicted by knowing their EKS score (low vs. high). Of the three intention components (i.e., A, SN, PBC), participants' attitudes (A) towards teaching evolution by natural selection were more likely to differentiate among the LL and HH groups when compared to their subjective norm (SN) and perceived behavioural control (PBC) scores. It appears that LL participants tended to underestimate both the negative aspects and the potential benefits of teaching evolution by natural selection when compared to the HH group. With regard to the interaction between participants' knowledge of evolutionary concepts and their perspectives on the nature of science, the results suggested no consistent or unique differences between the LL and HH groups using two independent measures of science epistemology.
Chapter 5

Results: The Simulation Discussions

For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath (Matthew, XXV:29).

Overview

In this chapter, sub-goal three, which was to analyze and to interpret the small-group discussions as group members interacted with the simulation, will be explored. Research question four (Would using a computer simulation of basic evolutionary processes in combination with small-group discussion be an effective way to reveal the nature of intermediate/senior pre-service science teachers' conceptions of evolution?), will also be discussed in this chapter.

To facilitate a structured analysis of the large volume of dialogue that was produced during the two occasions participants used the simulation (i.e., phase two and four), the discussions were divided into the most prominent events that occurred as participants used the simulation: 1) the actual execution of the simulation, and 2) answering questions related to the data produced from it. In phase two, the first time participants used the simulation, there were differences in how quickly each group was able to move through the steps required to execute the simulation (see Appendix E) and answer the questions. Consequently, not all groups were able to provide answers to all of the questions. Thus, for phase two (participants' first exposure to the simulation), the primary analysis will involve an examination of the verbal exchanges between group members as they used and explored the simulation (see Table 8, p. 63). The themes that emerged from these exchanges will be highlighted with one or two examples, followed by a brief explanation of the dialogue.

The other aspect of the phase two discussions that will be examined will be the one question that all groups were able to answer completely: "Is selection a phenomenon that happens to genes, to individuals, to populations or to species?" (see Table 8, p. 63). Again, similar to the previous analysis, the themes that emerged from exchanges will be highlighted with one or two examples and a brief explanation of the dialogue will be given.
In phase four of the study, (i.e., the second opportunity participants had to interact with the simulation), they were more familiar with its execution. As a result, there was very little disparity among groups in the time it took for them to move through the steps and to begin answering the questions. Thus, the analysis of the participants' dialogue during phase four will focus on the questions that all groups were able to answer; questions one to six (see Table 9, p. 66).

Also, for the purposes of exploring the discussions within each question for both simulation runs, the analysis will sometimes make use of participants' levels of knowledge (bottom, middle, upper of the EKS distribution), in order to highlight differences among groups and participants. To protect the anonymity of participants, they will be identified by referring to them simply as P1(a), P2(e) ... P19(h). The letters in parentheses are used to identify the group to which a participant belonged. Finally, some interesting findings emerged related to the nature of verbal utterances in the dyads and triads as a function of level of knowledge. These findings are of a quantitative nature and are discussed in the supplemental findings sub-section.

Phase 2 - Using the Simulation

The most obvious characteristic that defined the exchanges between groups members as they executed the simulation for the first time, and became familiar with its operation, was the relatively task-oriented nature of their responses. This was due mainly to the fact that the simulation was structured so that participants would perform the task of running the simulation in a more or less step-by-step fashion. Many of the exchanges reflected this ordered process, with participants asking brief questions of one another and making short comments related to the task at hand. The following exchange was very typical for the "procedural" aspects of executing the simulation:

*Group A*

P8(a): We're saving our second one. Now, we put in ..,

RM: So, that's like "time2.txt".

P8(a): "Time3.txt"

P4(a): No, it's time 3.

P7(a): No, we're time 2.
P4(a): Time 2..

P8(a): Oh.

P7(a): Aren't we...? Yeah, time 2, right here.

P8(a): Oh, I'm sorry we had, yeah, time 2 dot 't' 'x' 't'. Yeah, cause it's 't', 'i', 'm', 'e', two. Now, what do we do, 'e'?

All seven groups had exchanges of this nature, especially in the early execution of the simulation. Participants had been made aware of why they were doing these steps (e.g., to save the simulation data) and so understood that these were important to the goals of using the simulation. Therefore, they tried to ensure accuracy in their execution. Generally, all of the groups were able to complete the execution of the simulation successfully and required very little intervention or assistance from the author to complete the steps. In other words, there was nothing inherently complicated or difficult about running the simulation, nor were there any problems in executing the simulation that participants could not solve on their own.

Once the routine of how to run the simulation was more familiar to participants, the nature of their discussions moved towards making observations about the objects and events on the screen. Primarily, participants' exchanges involved making comments about the correspondence among what they could observe, what they thought they knew about the simulation from reading the manual, and their growing intuitive understanding of how they believed the simulation operated:

Group C
P1(c): Black's still eating green.

P13(c): I think the green is the food I think. Oooh, that's what it is.

P1(c): You're right.

P13(c): Alright, OK.

P14(c): Green is food, right? Green dot is food.

P1(c): Yeah.

P13(c): Green is maybe ..,

P1(c): Cause, the red and the black are ants. So what's white?
P14(c): Mutation? I don't know.

P13(c): Green is food.

P1(c): Does white ever get eaten?

P13(c): No ...

P14(c): It doesn't move.

P13(c): Oh, maybe the white is poison.

P1(c): Ooooh.

P14(c): Oooooh.

P1(c): Oh that's right.

P13(c): White is poison and green is food.

This discovery of the correspondence between the colours of the objects and their purpose or function occurred for all of the seven groups, but at different points in their conversations. Group C made all the correct connections about one-third of the way through the execution portion of the first simulation run. It is also important to note that P13's response ("No") to P1's question ("Does white ever get eaten?") is an indication that P13 read the manual. The manual (Appendix E) which accompanied the simulation contained information related specifically to how objects and events interacted with the virtual environment. Thus, the only way a participant would have known that poison remains fixed in the environment would have been as a result of reading the manual.

The next two dialogues cited are similar in nature to the discussion above, and took place between group members almost immediately after the simulation was executed.

*Group D*

P10(d): Yeah. Look at the ants. Where's the ..., where are they? The green ones?

P11(d): No, I think the green is the food.

P10(d): The black ones, right?

P11(d): The black and the red dots are the ants.
P10(d): There aren't many there.

P11(d): And, there's no anteater coming through. There's only the poison, the white is the poison but there's no grey anteater.

and similarly,

*Group G*

P18(g): Oh, look at all our ants. That's so cool, go guys, yeah, eat, yeah eat.

P16(g): So white is which?

P18(g): Green, food, white, poison.

P16(g): Black and red ants. The green is food, I'm assuming. What's black?

P18(g): Look at this guy go, he's mowing down on . . .

P16(g): [laughing]

P18(g): This is great! . . . Black is the black ants and red is the red ants, green is food, white is poison.

Again, all groups were able to sort out, relatively quickly, the properties of all the visible objects on the screen (i.e., ants, poison, anteater, and food).

Observations regarding events that occurred as the simulation continued to run revealed that participants were attentive to what was occurring on the screen. Many actions of the objects evoked excitement, curiosity, and surprise. In addition to these affective responses, an important cognitive theme emerged in participants' observations of these events. Often the observations were accompanied by ad hoc *speculation and hypothesizing*. In other words, it was not enough for participants just to observe events unfolding in the simulation, there was a spontaneous need to question and explain them, as well. A brief example is provided from each of the seven groups.

*Group A*

P8(a): Look at all the food he's got, but he's only got a small number, these guys who have less food have, like, all these ones.

P7(a): Maybe they expended the energy to have kids.
P8(a): Yeah, maybe all the... yeah, or maybe it cost them more food because they had kids.

P7(a): Yeah, yeah.

*Group C*

P14(c): There's only one got eaten? That doesn't make any sense.

P1(c): What'd you say?

P14(c): There's only one got eaten.

P13(c): See there was ..., I think most of them died by starvation because the food was only 500, so...

P14(c): Oh, yeah, yeah.

*Group D*

P11(d): Food, age. What's that age in days? Hours?

P10(d): [laughs]. What does that mean, parent 1, parent 2?

P11(d): Hmmm. I wonder if that's the number of times it's been a parent?

P10(d): I don't know.

*Group E*

P2(e): Oooh, they're pretty old ants.

P17(e): The red ones are older. Are they older? How are they divided? Just done by red ..., 

P2(e): Red blood. See if there is a red mutant guy. I'm not too sure about that. See here's the ones that were born.

*Group F*

P12(f): We started with 200 and we're down to 58.

P3(f): OK, and they had 500 whatever units of food and now they're down to 320.

P12(f): They're not consuming very long.

P3(f): No, something, something's wrong.

P12(f): They're conserving.
Group G
P18(g): Press 'c' at the main menu and save ant statistics. Press 'e', 'f', 'g' at the main menu and examine the statistics. OK, 'e', view the ant statistics. Ok, it looks like we're running out of red ants. We only have 28 red ants. Ok, 'e', 'f', most matings, most sharings, and.., kills, one of our ants had 36, not just 1 kill. I wonder what that means? Number of food, there's still four hundred and four food left. Starvations, 95 starvations. Total ant population, 48. Of, the original 200, we only have 48 ants left?

P16(g): Well, 95 died from starvations.

P18(g): One killing, zero matings.

Group H
P5(h): See, I'm thinking that not many ants are dying by poisoning anymore.

P19(h): [laughing]

P5(h): That's true.

P19(h): Yeah.

P5(h): I think all the dumb ants died already.

P19(h): There isn't many ..,

P5(h): The non-poison recognizers ..,

These dialogues show that the nature and focus of the queries was somewhat varied. Although, most were genuinely relevant to substantive conceptual issues (e.g., the exchange between P7(a) and P8(a) and between P5(h) and P19(h)). However, what was conspicuously absent in all exchanges among group members was any follow-up response to speculations or hypotheses posited. In other words, while important conceptual issues were raised via questions posed as participants interacted with the simulation, no answers from other group members were forthcoming.

Two other interesting themes emerged from the discussions that are noteworthy. First, there were several participants who provided distinct anthropomorphic responses to events in the simulation. Recall, that the screen graphics amounted to nothing more than numerous coloured dots that moved (ants - black, red) or were stationary (food - green, and poison - white). That participants tended to attribute human characteristics to these
dots, supports the idea that despite the lack of realism in the simulation, it was still highly involving cognitively.

Unfortunately, the tendency to ascribe human characteristics to such events and objects can lead to conceptual errors and misconceptions. For example, the ability of ants to avoid poison or to avoid the anteater had nothing to do with mental abilities. Rather, it was a consequence of whether an ant possessed a particular genotypic characteristic that was manifest as a particular phenotypic response in the given environment. As the next three pieces of dialogue reveal, participants thought ants could be “stupid”, “dumb” or “aggressive” and that the anteater could also be “stupid.” Interestingly, all these anthropomorphic terms are used pejoratively.

Group A
P8(a): Oh he's gonna eat, he's gonna eat, he's gonna, oh, he missed that one. He must have been able to see him. Nope we didn't have any stupid ones.

Group E
P17(e): Yeah, the anteater is a bit stupid.

Group G
P16(g): Is there a difference between the red and black ants?

P18(g): I don't know. I think it's just a way to differentiate between them. But I don't think any of them are more aggressive or anything like that.

Group H
P5(h): I think all the dumb ants died already.

The last significant emergent theme was somewhat of a surprise. All seven groups had exchanges that dealt with death, dying or killing. Numerous other aspects of the simulation were more salient and explicit (e.g., feeding, how ants moved, mating behaviour, food sharing) but none of these emerged as a prominent focus for discussion. The death theme emerged vis-à-vis the ways in which ants were most likely to die: eaten by the anteater, starvation due to lack of food, poisoning, and suicide. Ants could die in combat but this did not arise in any of the discussions.

Group A
P8(a): Let's see if he [the anteater] kills anybody.
Group C
P13(c): Some of them maybe died early [laughing].

P14(c): Or some got eaten.

P13(c): Some got eaten.

Group D
P10(d): Yeah. 60, 60 left.

P11(d): Oh, boy.

P10(d): Starvations, poisonings.

P11(d): Kills, mating, food-sharings, lots of food sharing going on. Crossovers, inversions .., No crossovers, inversions, or mutations. Wow.

P10(d): Many ants died.

P11(d): Many ants died [laughing].

Group E
P2(e): Look at them all go. Don't look like there's very many ants. What's the anteater? Any anteaters around here? Isn't it a grey dot or something? Oh, oh, there's the anteater. There he comes. See?

P17(e): Oh, that thing.

P2(e): It's like a Pac-man. [laughing]

P17(e): Does he eat ants?

P2(e): He hasn't run into any ants, he just goes in a straight line. I guess though the ants are pretty good, oooohh, that one ant almost ..,

P17(e): Where is it?

P2(e): I don't think it's there all the time.

P17(e): I want to see it eat!

Group F
P12(f): Yeah, sounds good. 'g' is the best one.

P3(f): Yeah. I say ..

P12(f): Oh we have a few deaths.

P3(f): Oooh, lots. Just go to 'g'.

P1(e): 60760 left.
Group G
P18(g): This guy's going to die. He's just sitting there. Have you seen the anteater yet?

P16(g): No.

Group H
P5(h): Oh, he's gonna ..., he's gonna ..., he's mowing!

P19(h): He's the anteater. We don't see that.

P5(h): Here he is.

P19(h): Oh, yeah, yeah, yeah. Ok.

P5(h): And, ..., [slurping sound] got that guy.

P19(h): Oooooh.

P5(h): He just passes by every now and then.

Phase 2 - Unit of Selection Question

The last question posed to participants as they completed their first session with the simulation was: "Is natural selection a phenomenon that happens to genes, to individuals, to populations, or to species? Please explain the reasons for your answer." (See Table 8, p. 63). Some time will be spent exploring participants' responses to this question because it is arguably the most important concept that must be understood by anyone hoping to provide a coherent and unified explanation for evolutionary events.

There were two noteworthy themes that emerged from these discussions. First, there was a tendency for group members to acquiesce to one another. That is, a very common reply from the other member(s) of the group was simply to offer supportive agreement. This type of reply tended to come from those individuals who had relatively lower EKS scores within the group. In fact, of the approximately 37 times acquiescent phrases (e.g., "yeah", "right", "I agree", "Uh hmm") arose in all discussions, 30 (81%) were uttered by participants who had relatively lower EKS scores within that group. Below are two examples of this type of interaction:

Group A
P4(a): So, selection, of course, at all different levels.
P8(a): But it's gotta start small.

P7(a): But, we would agree that it starts on the gene thing.

P8(a): Yeah, do you agree with this?

P4(a): Yeah.

P7(a): So you have the mutations, happening, mutations at the gene level, not at ..,

P8(a): Yeah, exactly ..,

P7(a): Not the species level.

P8(a): And mutations could be either good or bad.

P7(a): Right.

P8(a): And the good things .., I just used mutations as a such negative word. [laughing].

P7(a): The only way mutations were to happen at the species level, is or maybe at the population level is, like Chernobyl. You know ..,

P8(a): Yeah,

P7(a): Where the entire population ..,

P8(a): Wiped out. Yeah.

P7(a): is affected by radiation ..,

P8(a): Yeah.

Group H
P5(h): Well, for the two of them it's the same.


P5(h): For both ants, the environment is the same.

P19(h): Yeah, so there's always one that wins, like have the advantage and some genes, in black would give them good ..,

P5(h): But see you could also argue that it could have been one particular black ant that had the best genes ..,
P19(h): Yeah.

P5(h): and I'm saying it's possible that was the best ..., you know what I mean? It just happened to be, it just happened to be the black that survived and strived.

P19(h): Yeah ..., and ah, after ...

P5(h): And that case, it's not necessarily the population.

P19(h): Yeah, it's the genes. In that black population. So, you're talking ..., it might be the individual but then the stupid genes in there. As a matter of fact like behaviour ...

The second most apparent theme in discussions of this question was related to the substantive content of the question. For example, two of the seven groups (i.e., D and F) felt that biological entities other than the gene were the primary targets of natural selection. These two exchanges are discussed next. For the other five groups (i.e., A, C, E, G, and H), the gene was considered the target of natural selection. However, for four of these five groups (i.e., A, C, G, and H), the nature of how this was expressed by group members varied widely and was marked by uncertainty. This uncertainty was manifested by descriptive accounts of gene selection that lacked supportive explanatory reasons for the answers posited. The one group (E) that offered a relatively good descriptive answer for why they thought the gene was the unit of selection, failed to provide any substantive support with reference to the simulation.

*Group D:*

P10(d): I think selection happens in populations of the species.

P11(d): Yeah.

P10(d): Because when different populations live in different environments they are the same species ...

P11(d): No, I agree with you. I just think ..., I wonder if ..., these two ..., These two ant populations, or maybe it's just one ant population happens to be the red or black because you could have a population of people such as ourselves, some of us are blond some of us are dark haired, but that doesn't make us two different species. Uah, especially because the genes are the..., they're not the same but the possibilities of genes are the same.

P10(d): Uh hmm.
P11(d): Um, like there, they either can be blind or see food 15 squares away and the probability of the red ant is the same as the probability for a black ant to have any one of the 16 characteristics.

P10(d): Uh hmm.

Group F

P12(f): So you think that selection.

P3(f): Is a phenomenon that happens to ..., 

P12(f): Genes, individuals, populations, or species.

P3(f): It happens to all of them. Because they are all interrelated. I mean if the species is being affected it's because the population is being affected because individuals are being ..., because certain genes that make them better or worse suited to survive in that environment.

P12(f): Yeah.

P3(f): Right. So, it's everything.

P12(f): I agree.

For the groups that thought the gene was the unit or target of natural selection, the following two exchanges were typical. As noted above, these exchanges are best characterized as exhibiting some uncertainty and as being without any cogent explanatory support.

Group C

P14(c): It happens to populations. No, to genes.

P13(c): I think it is to genes. Right?

RM: How would you know that?

P1(c): I think the mutation occurs at the gene level.

P13(c): At the, yeah.

P1(c): So then a particular..., Well, the mutation at the gene, does that mean that population with that gene is selected for or does it mean that actual gene is selected for?

P14(c): It can happen for the mutation for the gene, right? Then that gene in the population depends on the mutation.
P1(c): Well, there's a selection for that population with that gene. But at first, you're not going to have a population with that gene. First, you're only going to have an individual with that gene. Then, there's selection for that individual, and then, you know ...

P14(c): Then the population.

P1(c): .., then the species. So, maybe um, the mutation happens at the gene level but it means the selection for either the gene or the mutation. I mean the gene or the individual. Which is it?

P14(c): Um, gene. Because either way you have to have genes in order to have some type of animal. Right? So you can't select if you don't have any..

P13(c): But that gene can be spread through the population by nature.

P1(c): Yeah, so that's being selected for though. It's not, you know what .., no, it is the gene. It's the gene that's being selected for. Because there are other parts of that individual that are necessarily selected for so that gene, that uah, that's one part of that individual that's being selected for.

P13(c): Yeah .., .

P1(c): So, ..,

P13(c): The gene.

P1(c): Selection happens to genes.

P13(c): Please explain the reasons for your answer.

P1(c): I don't know how to explain it to you using the graph stuff.

Group G
P16(g): It's the genes. Isn't it?

P18(g): Yeah, but ..,

P16(g): Individuals are representations of their genes.

P18(g): Right. But then the population, doesn't the population develop the characteristics of those genes?

P16(g): Yeah, but, ..,
P18(g): But it results from the genes. I'd go with genes because I think the survival of the population and the species would just kind of be carried on through the genes.

P16(g): I think it does.

P18(g): That's what we think.

P16(g): Because that's how natural selection works. The individual grows according to their genes.

P18(g): Yeah, it can't will itself to grow, ...

P16(g): It has to be the strongest to have those adaptations.

P18(g): Right. I agree. Go to ants.

The final discussion, presented next, contains an exchange that has some descriptive and explanatory ideas related to the gene-level view of selection. Again, however, their reasoning is not supported by reference to the simulation.

Group E
P2(e): At what level does it operate? Does it operate at the level of the gene, the individual, the population or the species? That's basically, I think the question. You see, I..., I would say, that selection ...

P17(e): I think it operates at the gene level but it expresses itself at the individual level.

P2(e): I see natural selection as survival of the fittest. That whole..., the important and imperative characteristics are being passed on. Maybe it being the biologist in me, I think of it in terms of genes, exactly. In terms of the genes that are passed on in terms of your chromosomal make-up, that's ultimately where selection occurs. It has influences on the species because it's what's going on in the species that dictates what genes may survive, what genes may pass on but ultimately I think selection occurs at the level of genes, it's ah, expressed at the level of the individual but it has influences by populations.

P17(e): I think the individual has an influence, too, though.

P2(e): Uh humm.

P17(e): Because one gene's survival depends on another gene.

P2(e): Yeap.
Phase 4 - General

The dialogues that were part of phase four represented exchanges that arose as a result of participants’ second interaction with the simulation. Table 9 (see p. 66) contains a list of the six questions that participants were asked to discuss during this phase of the study. Note that none of the questions asked in phase two was asked again in phase four. Different questions were posed in order to provide a rich sample of participants' thoughts on evolutionary concepts as they related to events in the simulation.

Unlike phase two, participants executed the steps of the simulation rather effortlessly and without many of the observations and comments that were characteristic of phase two. In other words, because they had become familiar with the operation of the simulation, participants could now focus their attention on the primary objective of this phase: answering the questions related to the data produced by the simulation. Recall that some of the analyses of the dialogues in this phase will involve a closer examination of how participants' scores on the EKS were related to the exchanges within and among groups. There were no equipment malfunctions during this phase and, therefore, dialogues from all eight groups will be examined.

Phase 4 - Question One

The purpose of this question was to explore how participants perceived randomness and its role in evolutionary processes. This question did not require participants to interpret data produced by the simulation. Instead, the question encouraged them to speculate about what might occur and to use their prior knowledge of how randomness operated to influence evolutionary events (see Table 9, p. 66). Seven of the eight groups attempted to provide a thoughtful response to this question. Only group G failed to give any details or supportive reasoning for their answer:

*Group G*

P18(g): Oh yeah, the first question. [Begins reading the first question]

P16(g): So, similar right?
P18(g): I don't think so. They won't be exactly the same. So, we continue.
OK, press 'a' to run. Wow!

Two distinct categories of responses emerged for the other seven groups: 1) Non-interaction, and 2) Interaction. All seven of these dialogues will be reviewed in this subsection because they provide good insight into how participants perceived a critically important, but often poorly understood concept in evolution, the gene-environment interaction. Four groups (i.e., A, B, C, H), had dialogues that were indicative of the non-interaction category. The other three groups (i.e., D, E, F) had exchanges that were characteristic of the interaction category. The first category of discussions, non-interaction, was characterized by a superficial understanding of randomness. That is, there was no clear indication that participants understood what was varying randomly in the simulation or how such randomness had arisen. Moreover, there was no explicit discussion regarding the influence of the environment and how it would interact with the ant genotypes to bring about changes in the composition of the ant populations over time. The only hint that anyone was aware of the importance of the gene-environment interaction was the fact that the anteater was seen to be a factor in some way. Below are excerpts of discussions from each of the four groups that belonged to the non-interaction category:

*Group A*

P8(a): Hmm, see if they [the other groups in the study] had all the same chromosomes, as our ants did, then I would say it would, but ...

P7(a): They don't.

P8(a): They don't.

P7(a): It's randomly, chromosomes are randomly generated.

P4(a): Yeah, they're randomly generated.

P7(a): So, we're going to have a different population.

P8(a): So, because we have different ones from them, then it's going to be totally different cause some of them might not see anteaters and or they, might have ..,

P7(a): Right.
P8(a): We feel sufficient with this answer.

P7(a): [laughs]. Please go to step two.

P8(a): OK.

*Group B*

P9(b): It's going to be unique.

P6(b): Because this is a random program.

P9(b): Yeah, but ..,

P6(b): If it's random, then any number of factors could change cause the computer is gonna randomly .., like that .., the number of times like the anteater comes in also ..,

P9(b): Yeah, that's right.

P6(b): So, it's gotta be unique.

P15(b): Yeah, ok cause it's random, everybody's going to have a difference.

*Group C*

P13(c): OK. I think if the computer.., don't say anything yet. I think, OK. The word here is randomly.., the word here is randomly. So, even though the environmental parameters and everything is the same, OK, and the population number and everything is the same, because, the computer generates those ants randomly, their genetic makeup is not going to be the same for each one.

P14(c): Yeah.

P1(c): I agree, yeah.

P13(c): So, we would have a different genetic makeup of a population or sample. We agree.

P1(c): I agree.

P13(c): So, it would be unique compared to other groups.

P14(c): I agree. Step two.

P13(c): You guys are just agreeing?

P1(c): No, no, no. I really agree.
P14(c): I agree.

P1(c): You summed it up really nicely. Number 2.

*Group H*

P5(h): A description?

P19(h): (laughs) Description. Yah. The description will be different.

P5(h): Yah, of how the ants will change over time. It will be different.

P19(h): Will ours be similar or .., [Reading part of the question]

P5(h): It will be different because the genes are random. Right?

P19(h): Yah.

P5(h): So how they progress through the .., through the ah .., thing.

P19(h): Yah, how they interact with .., .

P5(h): Will be different from the others.

P19(h): .., are completely different. I guess there is quite a bit of random chance there. Right?

P5(h): Yah, it's all random. Because all the genes are random for each population, like for each ant. Genes are random. Right?

P19(h): Except .. oh, well we set up .., it's a hundred red, a hundred black.

P5(h): Yah, there's a hundred of each. But among those hundred ants, each .., each ant has a random set of genes.

P19(h): Yah. Even though the initial .., .

P5(h): Everything initially is the same.

P19(h): .., is the same.

P5(h): But, it will change over time.

P19(h): Yah. I think so

P5(h): So, I say it will be unique.
The dialogues that comprised the interaction category were noticeably different. There was explicit discussion of what was varying randomly in the populations and how such variation had arisen in the simulation. Furthermore, there was specific mention of environmental factors and how these factors could potentially influence the ants.

In addition to being a good example of a discussion that falls into the interaction category, there is an interesting point to note about the exchange below between the participants in group D. P11(d) was the only participant in the study who consistently responded to questions with answers that indicated a very strong understanding of evolutionary concepts. Notice how, on four separate occasions, the other member of group D (i.e., P10) elicits these exemplary responses with questions that probe for P11(d)'s ideas.

*Group D*

P11(d): Well, it's going to be unique.

P10(d): Yeah, I think it's going to be unique because um, there are other environmental factors not just like ..,

P11(d): The environmental factors are the same, it's the genetic makeup of the ants that's different. Because the 200 virtual ants are, have been randomly generated, so some of them are going to be able to see food farther, some of them are going to be able to attack other ants, ..,

P10(d): Uh hmm.

P11(d): Some of them are going to be able to see that anteater or are poison resistant, but the proportions of each may be different in different populations so our population of ants may have certain ants that will adapt better to their environment and will survive better in this environment.

P10(d): What kind of environmental factors do they have?

P11(d): Well the environmental factors are all the same. We both, all the groups have a hundred red and black ants ..,

P10(d): Uh hmm.

P11(d): They all have 500 points for the initial number of food, um, the .., All the populations have maximum number of food of 500, they all have the same amount of poison, they all have the same number of crossover, inversions and mutations um .., So, I think all that's different is the genetic scheme of each of the ants that has been randomly generated. That's what it seems like to me.
P10(d): Uh hmm.

P11(d): So, I think that the outcome will be unique compared to other groups.

P10(d): Because they are different genetically?

P11(d): Yes, because, 200 virtual ants have been randomly created.

P10(d): Uh hmm.

P11(d): So, ...

P10(d): So, they have different genetic makeup and then they will respond to the environment differently, right?

P11(d): Yeah, like, if we can look at the food ..., Like, look at the chromosomes.

P10(d): Uh hmm.

P11(d): They're all red ants, but the chromosomes are different.

P10(d): So they will respond to the environment differently, right?

P11(d): Yeah.

P10(d): Because of different genetic makeup.

In the next two “interaction” dialogues, the exchanges reveal the emergence of a very important concept. For example, P17's comments hint at the possibility of “convergent evolution”. That a participant would consider such a concept shows an awareness of how important environmental constraints can be in shaping the emergence of adaptations. Moreover, the process of using the simulation appears to have elicited such a reflection.

Group E

P2(e): Which is the question that's right, so we're in the running section. [Begins reading the question]. I think it's going to be unique.

P17(e): Because?

P2(e): Because, we've got, although we have the same environmental parameters, you're getting randomly generated ants. So, the genotypes are going to be different, although the parameters may be the same if you look at the scheme, there's still ultimate possibilities, you know for these
different things so, what our computer creates may not be the same as what everybody else's creates.

P17(e): Uh, I sort of agree with that. Yeah, I agree with that I would just say thought that, ah, perhaps the changes are likely to be similar.

P2(e): Uh hmm., yeah, I would agree. Um ...

P17(e): But it depends on where you're starting from.

P2(e): Yeah, yeah. I think yeah, so, the actual changes that occur may be similar between groups because we do have the same parameters. But, it's unique in the sense that we are starting with different genotypes.

P17(e): Yeap.

P2(e): So, what ultimately ends up happening, that will be different.

P17(e): I agree on that. Shall we carry on?

Group F

P3(e): Well, I think it would probably be different because this thing is going to simulate different things for different groups I'm assuming. It's a random process, isn't it?

P12(e): Yeah, so if it's random, that would be different, that would be unique mutation, genetic mutations.

P3(e): I would think so. I would think so.

P12(e): To survive over others in the particular environment. Even though the environment is the same will depend on the genetic mutations that are occurring.

P3(e): That's right and the other conditions that the computer simulates like how much food there is ..., I'm assuming, I'm assuming that. I don't know. They'll respond the same way ..., 

P12(e): Cause we're not going to receive the same, like we're not going to have the same percentage of ants that say ..., 

P3(e): No.

P12(e): Are blind. It has the same ..., 

P3(e): Right, we don't know what combination of factors have been given to each group.

P12(e): How does ..., therefore unique.
P3(e): Right. Now, how does this timer work?

**Phase 4 - Question Two**

As noted above, understanding the concept of randomness and its influence on gene-environment interactions is a critically important "first principle" of evolution. The second question in phase four, which was composed of two parts, was used as means of exploring participants' ideas related to this concept from another perspective (see Table 9, p. 66). That is, instead of relying only on participants' prior knowledge of these concepts, this second question asked them to use the simulation data as the basis for their answers. In order to do this, participants had to make use of the graphs (e.g., see Figure 3, p. 62) as a focal point for their discussion. Thus, this question, and the remaining four questions, required participants to read and make interpretations of line graphs for data produced during the simulation.

First, although there were some minor differences in the groups' abilities and speed in reading the graphs, all were able to extract the correct information. Thus, all eight groups were able to answer correctly part 'A' of question two. That is, they understood that the virtual ecosystem had been seeded with a collection of ants, randomly generated by the computer, and they were able to state that this resulted in graphs that showed roughly equal proportions of phenotypic variants for the nine genes. However, for all groups, there was some confusion regarding the concept of randomness per se. The idea that some pattern of events could be unpredictable or that such events could occur for no demonstrable reason, other than chance, appears to have caused some consternation among participants. Below are three representative discussions regarding this theme:

*Group A*

P8(a): Avoid anteater? [The group begins examining the graph of "Avoids Anteater" genes]

P7(a): Yeah, try that.

P8(a): Both the same basically. Still really low too, eh?

P7(a): And this is at time 0 .., we're referring to again?
P8(a): Yeah. So ..., so then we think that a particular ..., they're same because statistically that's the way they set it up for us?

P7(a): Yeah, I'll go with that. I can't think of anything else.

P8(a): Nor can I. OK.

*Group B*

P6(b): Everyone is starting out the same cause we haven't the time yet for any of the ecosystem factors to interact on any of the ants. So, it has to be the same for everybody at time zero.

P9(b): No, I don't think so because ..., You have different ants. And each of the ants has a different kind of um, have different genes.

P6(b): Alright.

P9(b): I mean they all start off ..., it's the same environmental conditions.

P6(b): Yeah.

P9(b): But each ant has its own genetic make up.

P6(b): OK.

P15(b): That's also why you're going to get a random thing in the end right? Cause you're going to have a random number of genes.

P6(b): So why is it that they're all the same?

P15(b): That's what we have to figure out.

*Group F*

P12(f): So, they were ..., 

P3(f): Roughly, equal. And we saw that, right?

P12(f): It's just through randomness, isn't it?

P3(f) Yeah, that's what I'm thinking.

P12(f): So, why does this pattern exist?

P3(f): Why does this pattern exist? ..., 

P12(f): Just random um ..., generation of these ..., 

P3(f): But if it was random, why would it be equal?
P12(f): I don't know?

P3(f): If it was random, you wouldn't notice ...

P12(f): Why would it be equal though?

Answers to part 'B' of the second question revealed the same two categories of responses: 1) Non-interaction, and 2) Interaction. However, for question two part 'B', only one group (D) provided a response that fell into the interaction category. Recall, that a response was categorized as "interaction" if there was an explicit realization of the reciprocal interrelationship between genes and the environment in which they are immersed. The remaining seven groups (A, B, C, E, F, G, H) all had discussions that were categorized as non-interaction. That is, the participants' discussions implied that it was either genes or the environment that determined changes in the ant populations. To illustrate these two categories for question two part 'B', one discussion from each category will be examined.

Group D's response (presented below), as an example of the interaction category, was exceptional for several reasons. First, P11 provided exemplary responses that were supported with explicit references to the graphs. In other words, the graphs, coupled with sound background knowledge, appeared to have provided the necessary impetus and information for this participant to arrive at a coherent interpretation of the data. Second, P11's responses tended to be among the longest. In other words, P11 seemed to require relatively protracted responses in order for her to articulate her ideas clearly; her answers are notable because they are highly considered, reflective, and demonstrated her attention to specific terms being used. This was distinctly different from the kinds of responses provided by the large majority of respondents for this question. Typically, respondents would use only a sentence, maybe two, when giving answers. Third, it is difficult to interpret P10's role in the exchange. P10's relatively minimal contribution to this discussion is very different from the given-and-take style of exchange apparent in the non-interaction examples cited below. Last, P11's responses revealed her insight about a concept that emerged by examining the graphs as a collective. That is, she recognized that not only were genes interacting with the environment to affect their fitness, but also, that genes were interacting with each other to affect their fitness. In other words, it is the interactions of gene combinations that result in differences in the relative fitness among individuals. This is a highly challenging concept for most biologists to understand.
(Dawkins, 1982), and the simulation appears to have helped this participant articulate this idea very clearly. Group D's response to part 'B' of question two is as follows:

**Group D**

P11(d): I'm just wondering, how the fact that, the gene frequencies are roughly equal ..,

P10(d): Uh hmm.

P11(d): And that being caused by um the random generation of ants, or random generation of gene frequencies,

P10(d): Uh hmm, uh hmm.

P11(d): How that influences on what happens to the ants as they interact with the environment? Well, I think, starting off, ..,

P10(d): Uh hmm ..

P11(d): Well, put it this way, I think that none of them are, the only thing that's going to influence them is the environment in a sense because they're all, .., You're going to have equal amounts of each, or, or almost equal amounts of each type of ant. And, because of that, it's not like you have a larger population of one as opposed to another, so there's no bias starting off. They're all starting off the same, at least the same numbers in each gene group. And then the only thing that affects them is going to be the environment.

P10(d): Uh hmm. But look at this graph. The red ants have a better survival rate than the black ants, or roughly the same.

P11(d): Um, ..,

P10(d): Actually, the red ants with the up and down movement ..,

P11(d): Do better than ..,

P10(d): Yeah, they do better.

P11(d): Yeah.

P10(d): And then the black ants decrease.

P11(d): But you also have to think, I wonder if this is just .., If this is only, only has to do with .., Now, see that's the thing. Like I think red ants tend to do better overall. It's not necessarily just .., um, yeah, it's not necessarily just the cause, or just due to one particular gene. Like maybe a combination of all their genes together ..,
P10(d): Yeah, interaction between the genes.

P11(d): Yeah, will allow them to do better in the environment. So...[Begins reading the question again] Do you think your answer for part 'A' above has any influence on what happens to the ants as they interact in this ecosystem? Please explain your answer... Well, if they're starting off with roughly the same number of individuals with those gene frequency, or, with genes, then it's only the environment that affects them. Um, and it's only their interaction with the environment that will cause them to survive or not to survive. It's not the actual numbers in the population. It's only, it's only the genes interacting with the environment. They're not biased by the number of individuals in the population. At least for starting off.

P10(d): So, does the genetic makeup make the ants better in the environment or ..?

P11(d): Yeah, I think, I think the fact that .. You see, they're all starting off with um, about .. what 15 plus 20 um., and so, ..., basically the ants that happen to have the up and down gene will do better in that environment and it doesn't matter how many they've started off with. Like it's not like they started off with so many more ants. It's not as if they had 50 as opposed to everybody else had 25 ants. They're all the same, but it's just their genes help them do better in that environment regardless of what their initial population was, like, all the initial populations were the same. What do you think?

P10(d): Yeah, but the black ants with the up and down genes, they also didn't do that good. The population decreased also.

P11(d): Yeah, it could have been a result of another, of another gene, or combination of other genes as well. Cause, if you look at the other graphs, all the um, in general, the red ants tend to do better, than, like OK, we were at, looking at gene 4. Gene 6, [moves to that graph] you know, the red ants tend to survive more. Um, gene 10 [moves that graph], the red ants survive, the black ants don't. So, it might be a combination of a number of different genes put together that give the red ants um, you know, an advantage over the black. It might not, it's not just one particular gene I don't think. I don't know.

P10(d): I don't know. I'm not sure. I guess that's the answer.

P11(d): Do you want to leave it at that, then, we're not sure?

P10(d): Yeah, OK. Let's go to the next one.
As stated earlier, the non-interactive responses were characterized by an either-or perspective with respect to their answers for question two 'B'. That is, the interrelated and interdependent nature of genes and the environment was not fully acknowledged. All seven of the groups' responses for this category made direct reference to the graphs when providing support for their answers. There is one noteworthy point about the non-interacting discussion provided below. Towards the end of this discussion, P17 appears to convince P2 to give up the idea of the mutually interactive influence of genes and the environment for P17's notion of the predominant influence of the environment. Here is group E's response to part 'B' of question two:

P2(e): Ah, no, because they have the same average number of crossovers and stuff like that so ..., No, the thing that's different is their colour. How they ah, how an ant is generated ..., So, I don't know, I think that the answer for part 'a' has an influence on what happens to the ants because, I mean its genotype determines when, how much food they get, how long they survive in terms of eating and things like that and ...,

P17(e): Ummm.

P2(e): The amount of food that was eaten and the amount that survive would be very different if say, 50% of them were none [no movement genotype] and 50% were random [random movement genotype] because it does affect ..., 

P17(e): I don't know. I don't think that it does over time. Because, over time, we would expect the environmental variables to influence the results. So, therefore they would all end up with the same results no matter, no matter what they started at because, assuming the time was long enough. I mean if you look at this, you start to see the graphs are actually just levelling out and stabilizing. So, you have to think that maybe, even if there was quite a big bit of difference, it wouldn't actually change the results at the end because there's so many, there's enough generations there to ah, to normalize the results. What do you think?

P2(e): So, it has an effect initially but after time it doesn't matter?

P17(e): Yeah,

P2(e): Because the environment ..., 

P17(e): Well, these graphs seem to indicate that.

P2(e): The environmental parameters will control it, yeah.

P17(e): Because they stabilize.
P2(e): As opposed to the genotype. It, based on what is available in the environment. But, yeah, some do better than others. Those poor “none” guys [ants with a genotype that results in an ant that does not move unless it sees food] they're not doing well. They just basically died out.

P17(e): Soooo, ..,

P2(e): But in a sense then, it does have an influence.

P17(e): Why?

P2(e): Because part ‘a’. No, I guess not, OK.

P17(e): Well, over time it doesn't.

P2(e): Yeah, over time. I'm thinking of on a, more on a per ant basis, it's not very selective. Ok, ah, do we need to ..,

P17(e): Are we agreed on that then?

P2(e): Yeah.

Phase 4 - Question Three

The third question in phase four was used to discover how participants interpreted the word “need” (see Table 9, p. 66). This question was posed because individuals with a Lamarckian conception of evolution tend to hold the view that an organism's “striving to” or “needing to” survive or reproduce will be the sole determinant of its success. People who hold this specific misconception about evolutionary mechanisms inappropriately ascribe a human term (i.e., need) to biological events when the details underlying such events are obscured by using the word. In evolutionary theory, “need” has no status in nature. Need arises as an explanatory framework only because humans view biological events through a retrospective lens (Dawkins, 1991).

Generally, it is unclear from participants' responses whether the third question was worded in such a way that it was able to elicit their ideas about alternative interpretations of the word. Group C did hint at the idea that they should think more closely about what the term meant in a biological context, but no discussion surrounding this issue developed. Here is the exchange:
Group C
P1(c): There is a need to avoid. Yes, cause they seem to be dying off if they don't avoid. So, there is a need.

P14(c): Yeah.

P13(c): There was something on his paper about need and how it is defined in ..., we should ask him for help ..., There is a difference between environmental need like ah, not environmental need. There's something ..., 

P1(c): Which paper is that? Is that the ..., 

P13(c): Are you allowed to help us?

RM: Sure.

P13(c): OK, here it says, I know you wrote something in a paper about a need here. What does it mean?

RM: I want you to tell me.

P13(c): Is there a need?

P1(c): You want us to tell you if there's a need? Yeah, there's a need.

P13(c): [laughing]

P14(c): A biological need or a psychological need?

P13(c): No, I remember reading something else ..., 

The "something else" to which P13 is referring is a page on the Web resource where misconceptions regarding terms like "need" are discussed. Encouragingly, it was apparent that P13 had read the information, but unfortunately the details of her visit to the Web resource could not be recalled.

For the purposes of examining participants' responses to this question, a broader use of the word "need" was used to categorize participants' discussions. Thus, all groups were classified as adopting a literal interpretation of "need". That is, they examined the appropriate graph (i.e., the Poison-avoidance gene graphs), saw that there was a difference in survival among individuals with and without the gene, and concluded that "there was a need for ants to avoid poison". However, three groups (i.e., A, D, F) were able to extract important additional information from the graphs that five groups (i.e., B,
C, E, G, H) did not. Similar to responses to the first two questions discussed above, the important distinction that emerged was the recognition that simply possessing the "poison-avoidance" gene did not guarantee survival; other genes, in combination with the poison-avoidance gene, interacted to affect survival. It is again noteworthy that this critically important concept arose spontaneously with some groups in the context of the simulation. In other words, the "gene graphs" seemed to evoke in some participants a need to provide parsimonious interpretations of the data which included accounting for both confirmatory and apparently anomalous evidence in the graphs.

The discussion below is an example of the combination theme. It is also noteworthy because near the end of the exchange, P7 and P8 express a wish to explore some ideas they believed would help them understand these phenomena in more detail. This could easily have been pursued with the simulation if participants had been given more time or the opportunity to explore such speculations.

**Group A**
P7(a): Like, what does this show? This is the percentage of black ants that died and like ..,

P8(a): They had that gene.

P7(a): At this time, they died and they had this gene.

P8(a): Uh hmm.

P7(a): So, the majority of them to avoid poison at time 6, and died.

P8(a): But also, the ones that were alive had that gene too. So what do you think it means?

P7(a): So that would mean that there must be something else ..,

P4(a): Yeah, there must be something else ..,

P8(a): That's a very important gene.

P7(a): So, then the poison can't be that much important.

P4(a): Yeap, right, uh hmm.

P7(a): Once we see the two.

P8(a): I wonder if it would be if we increased the poison though, like if we increased the poison level? It probably would be.
P7(a): Yeah. That'd be nice if we could adjust it so that you could increase some of the parameters.

The next dialogue presented is another example of the combination category. Like the example above, there is no explicit mention of gene combinations, but the idea is strongly implicit as the participants try to interpret the graphs.

Group D
P11(d): OK, question 3 [begins reading the question aloud]. Oh, yeah, I think so.

P10(d): Yeah, of course. OK, actually, the black ants, see if they avoid poison, the population still decreased, right?

P11(d): Well ..,

P10(d): OK, let me see. Percentage of ants ..,

P11(d): I think that there's a need but it's not the only factor. I think that, you know the ability to avoid poison on its own is not an enough of an advantage because, you know the black ants, the black ants decreased anyway, so ..., It's not enough. But the red ants ..,

P10(d): So, the survival doesn't depend on only one gene.

P11(d): No.

P10(d): Depends on, like, the interaction between different genes.

P11(d): Different genes and the environment. So, um, So, there is a need, I think for poison avoidance, um, but it's not the determining factor in survival. I think it's ..,

P10(d): It's not the only one.

P11(d): Right, I think it's one factor um, which must be combined with other genes ..,

P10(d): It's necessary, but it's not enough.

P11(d): Yeah, exactly. That's perfect. Well, I don't know. I think that's the right answer.
**Group F**

P12(f): Something's going on here. The red and black are really different. I wonder why?

P3(f): Oh, it starts to come down. Hmmm.

P12(f): I don't understand. This is what I would expect.

P3(f): Hmmm.

P12(f): Cause these ones are dying off, so now these are producing ants that are similar to them.

P3(f): Right. That makes sense for the black ones .., but the red ones ..,

P12(f): Maybe we have some gene mutations going on.

P3(f): Or maybe some more of them get eaten by an anteater or something, so their gene pool is removed, right?

P12(f): Exactly. Other things come into play maybe, for the red ants.

P3(f): Maybe a disease or ..,

P12(f): Yeah, or maybe, more of the red ants are blind and they don't see their food.

Phase 4 - Question Four

The purpose of question four was to elicit participants' ideas about the term "adapt". Specifically, the question asked participants to use the simulation to explain the difference between using adapt as a verb (i.e., adapting) and using it as a noun (i.e., adaptation) (see Table 9, p. 66). Participants' responses to this question revealed a broad array of thoughts, speculations and misconceptions. Additionally, some of the exchanges among group members were long, lively, and frequently argumentative in tone.

Overall, the discussions revealed three themes: 1) *Conflated*, 2) *Not conflated*, and 3) *Lamarckian*. The latter two terms reflect categories that were not necessarily mutually exclusive. In this subsection dialogues representative of each category will be presented. First, an example of a group dialogue (i.e., group C) that typifies the *conflated* category will be discussed and presented. Second, only two participants (P11(d) and P17(e)) were able to provide responses that were considered to be *non-conflated*. Importantly, both of these individuals made extensive use of the simulation as the frame of reference for their
answers. P17's discussion will be used to illustrate the non-conflated category. Last, two examples of the Lamarck category will be discussed and presented.

Seventeen of the 19 participants' responses fell into the conflated category. That is, most participants were unable to distinguish adequately between adapting and adaptation and frequently used the terms interchangeably, sometimes without awareness of doing so. Most participants' attempts to incorporate the simulation data to support an answer of this type seemed to occur on an ad hoc basis rather than as the foundation for an answer. For example, the discussion among the members of group C, cited below, was characteristic of the exchanges categorized as conflated. Eventually, the members of this group became frustrated with their attempts to resolve the terminological debate and gave up pursuing the question. No consensus appeared to have been reached and it is unclear to what extent their understanding of the distinction between the terms had been altered or improved.

*Group C*

P13(c): You know, “P1” I think you have a very good start at the beginning when you said the word adaptation is only used in a natural selection. When we use the word adaptation, we're talking about how certain genes are, that can, that can, well, adapt to the environment, right, are selected. So, it is the gene, we are talking about like successive generations.

P1(c): Yeah, yeah.

P13(c): But when you're talking about adapting, it's the gene is already expressed and it's adapting as in verb, you know what I mean?

P1(c): So, OK, yeah. OK, so you're right. OK, so it's an adaptation, that means the environment is selecting for the something that the, the population already has for a particular gene they may have, versus, adapt as a verb, means that within successive generations we're going to see an increase in, or everything, you don't see very much adapting, the verb, going on.

P14(c): I was thinking, adapting as a verb, is saying that an ant seeing or it got killed on poison, now is adapting to its environment, but has an adaptation, meaning it's seeing, but, it may not be necessarily avoiding, avoiding .., you know what I mean?

P13(c): Uah ..,

P14(c): Are any of you listening to me?
P13(c): Yeah, we're listening, we're listening.

P1(c): Yeah, we just trying to think of what, OK what were you saying, P14? Seeing, you said something about seeing.

P14(c): The ant is adapting to its environment, meaning it may not be necessarily born to be avoiding the poison, but it's seeing the poison. Like some ants, see far ahead than the other ones.

P1(c): So, how ..., was it adapting to seeing that?

P14(c): So, looking at the graph, the black ant seeing, the red ants, so saying that the black ant is adapting to its environment, while the red ant is not necessarily, have a longer sight, whatever.

P1(c): Yeah, but how do we know that's, there, that's the verb adapt as opposed to there's an environmental selection for the red ant cause it already had that gene?

P14(c): I think, I think, he wants us to have our own definitions of adapting and adaptation. So, ..,

P1(c): So, so, from the graph how could you tell though, that if it's adapting, a verb, or if it's adaptation, the noun?

P14(c): Because I can see that, from the graph, and because the black ants increase .., are the least adapted, ..,

P13(c): Why don't we stop here.

In contrast to discussions that fell into the conflated category, there were two participants who were able to articulate the distinction accurately. These responses formed the basis of the non-conflated category. Below is the discussion that included P17(c)'s conceptions of "adapting" and "adapt". Although the discussion is somewhat long, it is included here because P17 was the only participant to recognize that the graphs, per se, could not be used as evidence in defining the term "adapting" but could be used as evidence for defining what was meant by "adaptation". Unfortunately, P2's contribution to the exchange appeared to be tangential. Twice, once early in the conversation and once near the end, P2 tries to summarize what has been said and is only able to contribute to the dialogue by suggesting that "adapting" is a good example of a verb. In other words, there is no way to tell from this exchange the extent to which P2 has understood what P17 had explained about distinguishing between these two terms.
Group E
P17(e): For ..., so, for instance here, if they were adapting, ...

P2(e): They would learn how to ..., 

P17(e): They would learn how to avoid ah ..., 

P2(e): The poison, in order to survive. 

P17(e): Yeah, if they all had the adaptation that they could avoid the poison ..., 

P2(e): They would all survive. 

P17(e): They might all survive. If they umm.. it's hard to explain that. 

P2(e): Well, I mean, here's, if you look at it in terms of a verb and a noun. A verb is an action word. So, adapting is an action word, it's something that you're doing as opposed to the adaptation, which is a noun, I mean ..., now we're looking ..., 

P17(e): Yeah, ..., If they were able to learn, that that poison wasn't good for them, and then changed their behaviour, that would be adapting. 

P2(e): Right, because it's performing an action. 

P17(e): But the adaptation would be its ability to learn that. 

P2(e): [Repeats his words]. The adaptation would be the ability to learn. 

P17(e): Yeah, because that, that would be the inherited characteristic. It's the ability to learn to avoid poison. Whereas, the actual adapting ..., 

P2(e): No, but that's something they would pass on. 

P17(e): Yeah, they would pass on the ability to learn to avoid poison. 

P2(e): So, they pass on the ..., . 

P17(e): But the adapting is the actual avoiding, of learning, the actual doing of it. 

P2(e): Right, and the result of the adapting is the adaptation or whatever it is that comes of it and that's what's passed on. 

P17(e): Yeah. 

P2(e): OK.
P17(e): So, in this case, uah, so in this case, in this chart, they didn't have, they didn't have the adaptations that would allow them to adapt to the new poison, to defend themselves.

P2(e): OK. Right.

P17(e): So, when they ate the poison, they all died.

P2(e): Right.

P17(e): They didn't have the adaptation and ..,

P2(e): And in this situation, if they were to adapt, what would have to happen is that they would have to realize that ..,

P17(e): Yeah, they would either have to um, the adapting would be either learning to avoid the poison or it would be consuming the poison, and putting up with it, but they would have to inherit something to enable them to do that.

P2(e): Right.

P17(e): And that would be the adaptation.

P2(e): OK, and the adaptation is what is passed on.

P17(e): Yeah.

P2(e): The adapting is the action, the verb, the right now, we're doing this. So, it's almost like adapting is the changing of the behaviour or changing of whatever, and it's more of ah, it's a gradual process, kind of ah ..,

P17(e): So, in this graph, they don't actually really do any adapting.

P2(e): No.

P17(e): They have the adaptation.

P2(e): Those who have ..,

P17(e): They have the adaptation and that's it. There's no adapting.

P2(e): No, nothing has changed.

P17(e): Are we all finished with that question?

P2(e): Yeah.

P17(e): OK.
Finally, all eight groups had exchanges that fell into the Lamarckian category. What is unique about this category is that whenever a Lamarckian-type statement was uttered, sometimes it would go unchallenged, unrecognized as problematic, or even accepted as correct. Four groups (A, C, G, H) exhibited this pattern of responding to Lamarckian statements. Other times, Lamarckian statements were questioned or challenged by a member of a group which often led to lively and protracted exchanges as each discussant tied to argue their case. Four groups (B, D, E, F) contained discussions of this type of "challenging".

The first dialogue is an example of an exchange where both group members are unable to recognize their misconceptions and, indeed, even endorse one another's Lamarckian ideas. This example was typical of the four groups exhibiting the Lamarckian "unchallenged" type of exchange.

P19(h): Because if you can't avoid it, you die. So, what's the next one? [Begins reading question four out loud.] OK, wow, this is a tricky one. So, I guess it's how you interpret ..,

P5(h): [Begins reading the question out loud.] OK, I know what the difference is. The difference is, saying it's adapting to its environment means it's making a special change to that environment, itself.

P19(h): Within itself, yeah.

P5(h): As a noun, it's making an adaptation that works for that environment.

P19(h): Yeah, so. We see it as a process of adaptation. But if it's adapting then, it's like ah ..,

P5(h): That's the process.

P19(h): Yeah.

The next dialogue is an example of a discussion where two group members, P9 and P15, have begun to question P6's Lamarckian sentiments. This discussion is noteworthy because it shows how utterly resistant to change Lamarckian conceptions can be for many people. P9 and P15 try to explain the distinction between adapting and adaptation by using the simulation data as a reference and by using changes in red blood cell counts as a result of a change in altitude as an example. P6 appears to be following and accepting the arguments. However, the second to last comment that P6 makes,
reveals that she has not attained a Darwinian conception of the two terms. Again, although this dialogue was longer than most, the discussion was typical of the four groups which exhibited challenges to Lamarckian statements.

P6(b): Yes, these guys have an adaptation which allows them to be better than the red ants. And we'd need to look at another graph to show how they are adapting to their environment. There's a difference between adapting to your environment, OK let's put it this way. You and I, if we went to live in the mountains in Switzerland, OK. You and I would adapt our blood levels to better retain oxygen. That is adapting to your environment.

P15(b): That's a physiological adaptation.

P6(b): Right.

P15(b): But ..., 

P6(b): But these guys have adapted, or have an adaptation such that they see better than the red ants. There's something genetic that says that these guys see better than these. That's the difference between an adaptation and adapting to your environment. I think of an adapt, adaptation ..., 

P15(b): No. I don't ..., 

P6(b): As being something genetic. Whereas, you can adapt to your environment.

P9(b): No, but you can't ..., but the thing ..., But you don't change. You can't change a genetic make up in response to the environment.

P6(b): But your body can physiologically change.

P15(b): But your genes can't.

P9(b): Not for a population.

P15(b): But, your genes ..., No, no, pop ..., That's why populations evolve and individuals don't.

P6(b): Yeah, right.

P15(b): Like if you go somewhere else and you go to live in the mountains, yeah, you're going to increase your red blood cells. But you're not going to increase your genes. You're not going to change any of your genes. Like those, ..., 

P9(b): Uh hmm.
P15(b): .., are put regardless of where you go and if you don't have the genes that make you better adapted to the place, then you're going to die.

P6(b): OK, true enough.

P15(b): OK, so I think we're back at the beginning now.

P6(b): Alright, so an adaptation is something that this population will genetically possess.

P15(b): Yes.

P6(b): And as they are adapting to their environment, they are changing their genetic makeup to reflect ..,

P9(b): No.

P15(b): No.

P6(b): No?

In summary, it was hoped that the concept of “range of reaction” would emerge in the discussions of question four, but it did not. Range of reaction is the evolutionary equivalent of an organism's capacity for responding, reacting and, as P17 noted above, adjusting to its environment with some degree of flexibility. The terms responding, reacting, and adjusting are synonymously equivalent to “adapting”, but are much less likely to confuse students. Instead, as these discussion indicated, “adapting” and “adaptation” tended to be conflated, leading to misconceptions regarding how adaptive change occurs in populations over evolutionary time.

Phase 4 - Question Five

The purpose of this question was to explore participants' conceptions of natural selection (see Table 9, p. 66). There is wide agreement among biologists that natural selection is a process that results in adaptively functional changes to the relative frequency of genes (replicators) in a population (Dawkins, 1991). This is accomplished through the nonrandom elimination of organisms (vehicles) that possess relatively less successful allelic variants (Dawkins, 1991; Mayr, 1997). Hence, the fifth question in phase four is almost identical to the “selection question” examined in phase two, discussed earlier (see Table 8, p. 63). Recall that an analysis of the discussions for that
question revealed that two groups (i.e., D, F), felt that biological entities, other than the gene, were the primary targets of natural selection. The other five groups (i.e., A, C, E, G, H), suggested that the gene was the target of natural selection. However, only group E provided a well supported answer.

The analysis of responses to the question regarding natural selection in this phase revealed three mutually exclusive themes: 1) Gene, 2) Individual, and 3) Mixed. As the names suggest, responses were categorized according to whether the exchanges focused on the gene, the individual, or some mixture of the two as the target of natural selection. Overall, one group (i.e., D) had changed its perspective to a gene-level view of selection (from a species-level), while five groups (i.e., A, C, E, G, H) maintained their gene-level perspective. This time, group B was included in the analysis and their perspective was that the individual was the target of selection. Last, group F continued to espouse a mixed view. Again, due to the importance of this concept to evolutionary processes, examples of all of the groups' responses will be examined.

The dialogue presented next typify discussions that fell into the gene-level category. The group makes an explicit connection between possessing the gene and subsequent success in the environment.

**Group A**

P7(a): Yeah, we should be able to get that one. Just pick up any graph. Seeing genes say, number 3.

P8(a): Number 3.

P7(a): See, that's weird. I would have thought, like seeing, if the farther you can see ...

P8(a): Uh hmm.

P7(a): Then, oh, wait a second now. Farther they see, I'm wondering if, I'm wondering if they can only see between 12 and 15, but they can't see anything before that.

P4(a): Yeah.

P7(a): So that means he's gotta travel a larger distance in order to get his food but he's more susceptible to getting poisoned or eaten by other things right?

P8(a): But the guy 4-7 is the one that's more successful.
P4(a): Yeah, but, look at ..., see, 0 means it's blind too.

P7(a): Right, and 3 is that he only sees a short distance. So, he only has a short distance to travel.

P4(a): Yeah.

P7(a): Whereas the pink [the pink line on the gene graph]

P4(a): So, ...

P7(a): It's in between, not too far to get killed or not too short not to eat anything. So, we could use that as an example to answer that one.

P4(a): Yeah, that was a good example.

P8(a): So, because that was the successful length to see, natural selection happened because its offspring ..., they were more successful.

P7(a): Right. So, he, he transmitted that to his offspring.

P4(a): Uh hhmm.

There are additional aspects of group A's dialogue that must be noted. First, early in the discussion, P7 finds it "weird" that ants with genes that permitted the longest vision were not surviving as well as ants with genes for less acute vision (e.g., could only see food 4-7 or 8-12 squares away). Rather than entertain the possibility that genes for seeing food at a distance were interacting with other genes to promote survival, this group generates an ad hoc rationalization (i.e., "they can only see between 12 and 15, but they can't see anything before that") that allows them to maintain their non-interactive, single-gene perspective. Second, P8 suggested, "So, because that was the successful length to see, natural selection happened because its offspring ..., they were more successful." The causal chain of events implied in this phrase is the reverse of what actually transpires in nature. In reality, natural selection (nonrandom elimination) occurs first. The result is that humans observe differential survival and/or reproduction among gene-vehicles with various combinations of alleles. Only after this "filtering" has occurred can those phenotypic traits (e.g., "length to see food"), which are the product of the organism's genome, be judged by human observers as more or less "successful". P8's error is subtle but extremely common.

Unlike group A, group C does not try to use ad hocery for what appears to be an anomaly in the data. Near the end of the discussion presented below, P13's last two
comments show how this participant was seeking evidence to explain the possibility that other genes (e.g., the "attacking genes") may have been at play in determining the pattern of survival apparent in the "seeing-gene" graph.

*Group C*

P13(c): OK. So, how do we explain that? Natural selection .., Food levels, seeing genes, natural selection for that. Graph number 3 [See example graph below]. .., So, OK, what was the question again?

![Graph](image)

P14(c): Five?

P13(c): Which one do you guys wanna go to?

P1(c): Does it resemble evolution by natural selection?

P13(c): [Begins rereading the question]. Yes ..,

P1(c): Where we see the graph actually rising so that there's a higher percentage of ants with a certain gene. That .., that would show evolution by natural selection.

P14(c): Yeah, yeah.

P13(c): So, which ones were selected? In this graph, we're looking at graph number 3.

P1(c): So the red ants were selected. The red ants were selected. The red ants with the seeing genes.
P13(c): With the seeing, ah, like, ..,

P1(c): The seeing 12-15 squares ahead. They're selected for.

P13(c): But why, what about the 8-11, right? The ones that see are almost blind?

P1(c): I wouldn't say the other ones were necessarily selected for, they pretty much stayed constant.

P14(c): Yeah, the 12-15 seems to be selected for.

P13(c): Then we need to look to the other one. The easiest one. I wonder what .., attacking gene ..,

As noted earlier, P11 provided consistently superior answers throughout the study and the exchange presented next is no exception. When her argument using the graphs from the simulation failed to convince P10, she resorts to a simplified personal example to emphasize her point. P11 even makes herself the target of the “monster” to assist in her attempts to persuade P10 about the significance of a gene-level perspective.

Group D
P11(d): Uh hmmm. OK, so .., . Do you think evolution by natural selection occurred? Well, we started off with similar um, numbers of ants to begin with at time 0. And as time progresses, one particular gene pool..

P10(d): Gene, uh huh.

P11(d): tends to dominate the population, um, where the other ones tend to decrease. So, I think, I think that evolution by natural selection may be a bit, .., I think that natural selection is occurring. I'm not sure if the population is evolving so soon, but, we'd have to, I think we'd have to take it to a number of, you know, more generations. Let the time trials really go on until you have one particular, um, ant dominating. And I think ..,

P10(d): But do you think, like, natural selection is random here from the graph? It's not random, right?

P11(d): See, natural selection, itself, is not ..,

P10(d): Is random.

P11(d): What's random is the um, the occurrence of crossovers, mutations, that sort of thing is random. The process of natural selection itself is very methodical. Like, if you have a character trait that helps you survive, then you survive. Period. And you pass on your genes. Like, it's very
methodical. So, I think in this particular case evolution by natural selection is occurring in the sense that you have an initial population where the gene frequencies are evenly distributed and then over time, because one particular gene frequency allows, or gene allows for a population to survive, namely seeing food far away, and that population will increase, or that gene frequency within the population will increase.

P10(d): But for the black ants, if they have the better genes, like they see very far, they still don't survive.

P11(d): Maybe because there are other, in combination with other factors, they may not be competing as well with the red ants. See, I'm not really too familiar with this. The problem is I don't know if maybe there are ... they, I'm wondering what exactly it means to be a red ant or a black ant.

P10(d): Right. Where, there's only two or three generations here maybe. Not many.

P11(d): I'm not sure, because 'T' is simply time, it has nothing to do with generations. So, I think that there is some evolution by natural selection occurring because of the fact that you're getting a certain, ...

P10(d): So, OK, if there is only, like 2 or 3 generations, would natural selection happen within this short time?

P11(d): Yes. Even in one generation you can get natural selection occurring. Because if you, even in one generation, like let's say, you and I, um, difference between us ..., I have kind of brown hair and you have black hair. Some monster comes in and decides to start killing off all the people with brown hair. K, so, I die and you survive. So, natural selection in a sense has occurred. Um, even in just one generation, even if you don't see the necessary results, you'll see the dropping, let's say you have two lines here. People with black hair and people with brown hair. All the people with brown hair die, so the next time period, you're going to see a drop.

P10(d): Right.

As noted earlier, group E's, G's and H's discussions are oriented towards a single-gene view of selection. This perspective is not necessarily incorrect, but given the way in which the simulation operated, it is highly probable that these three groups have either missed or ignored a pattern in all the gene graphs that indicated interactive, gene-level effects of selection on the virtual ants. These three discussions are presented together without further comments.
**Group E**

P17(e): What's the question again?

P2(e): The question is, "Do you think anything resembling evolution by natural selection occurred with the population of red and black ants? Please explain the reasons for your answer.

P17(e): I think there was.

P2(e): That natural selection was occurring?

P17(e): Yeah, because umm . . .

P2(e): When you're looking at it there because at time 4, when the environmental factors changed, then, on the strength graph, those with the strength of 2, and 4 increased in numbers, for the black ants, and those with 1 and 3, has kind of declined. So, you're saying . . .

P17(e): Well, I thought 2 . . ., it definitely showed an increase, ah, when you changed the variables, . . .

P2(e): And we're saying that would be then because those with the strength of two were adapted and passed on the adaptation.

**Group G**

P18(g): OK, back to this . . ., the seeing one [gene graph]. The only thing that I can see that would support natural selection here, is that the ants that don't see well, their percentage total anthood, or whatever, is decreasing as time goes on. So, they start out with about the same levels as everyone else, the percentage of ants that can't see well. But then as time goes on, the percentage of ants that can't see well decrease and that could just be because they can't see the food and they can't get to it. Whereas, the population percentage of ants that can see the best, like that can 12 to 15 blocks away, is steadily increasing. So, the ones that don't have the good eyesight are decreasing, while, the ones that do have good eyesight, are taking up a larger percentage of the prop . . ., larger . . ., ant population.

P16(g): Right, and this is showing in all the graphs.

P18(g): Yes. So, that would support natural selection.

P16(g): True.

P18(g): Cause we see a gradual change as time goes by in support of the favourable characteristics.

P16(g): Exactly.
P18(g): Ok.

**Group H**
P19(h): [Begins reading the question out loud]

P5(h): Ok. I can give, one, I know it says to refer to one or two but I can give one for sure. Um, one is for the poison.

P19(h): Yeah, so we'll take a look. Which one is poison, S?

P5(h): We really don't have to take a look. Obviously that gene won't even exist anymore.

P19(h): Avoid, ..., So, the ones who can avoid, who are adapting right ..., But why's it increasing?

P5(h): I'm just saying the gene died. Like the gene went "ka put" ..., 

P19(h): Yeah. Because of the ah ..., 

P5(h): So, I would say that's a natural selection, adaptation. 

P19(h): Yeah, yeah. The, ..., if you have the gene, that can adapt ..., 

Next is the discussion by group B, who felt that the *individual* was the target of selection. The language in this dialogue is distinctly different from those presented above. Thus, despite the fact that all of the graphs were dealing with various ant genes, P15 suggested that "the ants that had the adaptations" (my emphasis) are subject to selection. Later, P15 asks a question that begins to orient the discussion back towards a gene-level view, but P9 makes reference to "the number of ants" not the proportion of genes, and P15 acquiesces to the use of this terminology. Their language subtly endorses the view of the *individual* as the target of selection even though the group members are viewing gene graphs.

**Group B**
P15(b): So, over time. Ok, so, ok, let's clear something here. Evolution by natural selection means that the ants that had the adaptations that make them better adapted to the environment will ..., 

P6(b): Be selected for. 

P15(b): Will be selected for ...
P9(b): Selected for...

P15(b): They will reproduce and pass on their genes.

P6(b): And pass on their genes.

P9(b): That's right.

P15(b): So, do the graphs have to show that over ..., as each population increases, that gene has to increase in frequency?

P9(b): The number of ants yeah, with that gene, yeah.

P15(b): The number of ants with that gene has to increase and the number with the other gene has gotta drop.

Last, group F's discussion was categorized as mixed. This group's exchange contained language that indicated they believed natural selection operated on both genes and on individuals. P12 jumps back and forth between a gene-level view (e.g., "So, in that particular environment, that gene is necessary") and an individual-level perspective (e.g., "The black are surviving better overall"). As noted, the graphs are in fact showing which genes in the black ant population are represented in greater proportions relative to other genes in the black ant population. P3 exhibits a similar tendency of adopting both a gene-level and individual level perspective.

Group F
P12(f): What question are we supposed to answer? [Reads question again ..., ]. Yes.

P3(f): The ones that were able to avoid the poison ..., were able to ...

P12(f): Survive more than the others.

P3(f): ... live. Now they had more food though. So, that was a factor, and so that's why were able to mate more, as well. So, there was more of them around. But the fact that they were able to avoid the poison is one ...

P12(f): Yeah, that was one.

P3(f): That's right. Anything to do with the anteater or ...

P12(f): So, in that particular environment, that gene is necessary.

P3(f): Yeah.
P12(f): Cause, there's poison out there.

P3(f): What about the anteater?

P12(f): K, let's say, here then, to ..., sharing.

P3(f): Avoid anteater genes and then the seeing other ants' genes.

P12(f): See, again, the black, the black are ..,

P3(f): Black are better able to avoid the anteater.

P12(f): The black are surviving better overall.

P3(f): Uh hmm.

P12(f): Their characteristics fit this environment better than the reds.

P3(f): Uh hmm. So, they're being selected.

P12(f): That's right. Let's try to sum up this one.

P3(f): Ok. Question 6, is that what we're going to?

P12(f): 5.

P3(f): 5. Yeah, we said yes.

P12(f): It says, explain the reasons for your answer.

P3(f): Well, our biggest um, biggest support for that is the fact that, there were more ah, black ants, they were able to avoid eating poison more, so therefore more of them were living. They also had more food. They seemed to have enough food that they needed to be able to mate. Whereas, the red ones didn't.

P12(f): They had more of the mating genes. They had all these things necessary to survive in this environment ..,

P3(f): That's right.

P12(f): ... surviving over the red ants.

P3(f): The red ants, that's right. So, that's ..,

P12(f): So, yes.

P3(f): So, yeah, yeah.
Phase 4 - Question Six

Dawkins (1982) showed that fitness is one of the most difficult and frequently misunderstood concepts in evolutionary biology. The purpose of this question was to explore participants' conceptions of fitness (part 'A') and to see if the simulation could assist participants with adopting an interactive, gene-level view of fitness (part 'B') (see Table 9, p. 66). Overall, a similar, but not identical, theme of responses emerged for part 'A' when compared to the pattern found for question five above. That is, part 'A' of question six revealed that participants' conceptions of fitness fell into four overlapping categories: 1) Gene, 2) Individual, 3) Mixed, and 4) Bravado. Only group F's dialogue contained exchanges that were exclusively of a single theme (gene propagation) for part 'A'. The other seven groups had exchanges that could be classified into two or more of the four categories. It may seem odd that the groups' discussions could be cross categorized. However, when talking about evolutionary concepts, it is very easy to lose focus of central concepts and to use terms or phrases that convey misleading and sometimes erroneous ideas. In other words, accurately expressing evolutionary concepts with language that correctly illustrates the causal chain of events as they transpire over time can be a challenging task. Each of these four categories will be discussed and one or two exchanges that typified the respective themes will be presented.

All of the groups, but H, had exchanges the fell into the gene category. These discussions were characterized by the idea that possessing a particular gene conferred a survival or reproductive advantage on its possessor. This advantage resulted in an increase in the number of individuals in the population who would have these genes. Importantly, a gene's success was seen as inextricably linked with the environment in which it was expressed. Discussions in groups B and F will be used to illustrate this theme. Group B's exchange is interesting because they express their theoretical ideas about fitness first and then look for evidence in the graphs to support their ideas. Group
F's dialogue is noteworthy because they are emphatic about the influence of the environment's role in determining an individual's fitness. Furthermore, they humorously reject the notion of “fitness is bravado”.

*Group B*

P15(b): When answering this question, please try ..., . Please try to ..., Survival of the fittest. OK, survival of the fittest ..., means that ..., 

P6(b): The best, the ones that are most adapted and best equipped to genetically pass on their genes and to survive in that environment will survive.

P9(b): Then that ..., 

P6(b): Best adapted wins.

P9(b): In that particular environment with those criteria.

P6(b): With those conditions. If something were to change, ah, for instance, an ice age. Then, you are selected against.

P15(b): Well, not necessarily.

P6(b): Unless you were a woolly lama and then you could survive or something.

P15(b): Yeah, if there's, yeah. So, provided those environmental conditions stay ..., 

P6(b): Are stable, ..., 

P15(b): And these genes will continue to survive but if anything happens to the environment.

P6(b): The environment. ..., 

P9(b): Yeah.

P15(b): Where these genes are not going to help them, the adaptations ... 

P6(b): Yeah

P15(b): They need different adaptations and the ants with the other adaptations will start to increase and these guys will drop.

P6(b): Unless these guys manage to ..., 

P15(b): Unless, no. They have to have the genes.
P6(b): That's right. That's right.

P15(b): So, if the majority of them don't have the genes, ..

P6(b): Then another ant population will increase.

P15(b): Another population will increase and those ones will drop.

P9(b): OK. Let's see if we can find something to back this up. One or two of these genes graphs.

**Group F**
P12(f): Again, we must refer to one or two graphs. [Reads the question]. Well, black. Same as what we were just talking about.

P3(f): Same as just what we were just talking about. They have a combination of characteristics or traits in their genes that allow them to survive in that environment better.

P12(f): Over another.

P3(f): They can avoid the anteaters better, they can avoid the poison better, they can share their resources or food more readily, so therefore they're helping each other, um, they have adequate food, and they can mate better.

P12(f): They have the mating genes.

P3(f): Well, the other ones have the mating genes, too, but they didn't have enough food for whatever reason available to them.

P12(f): So, we're saying survival of the fittest, ..

P3(f): In this case the black ants, ..

P12(f): Means having the characteristics, or genes, um, genes that give them an edge over the other ants that don't have it.

P3(f): Yeah, yes.

P12(f): And they're surviving more. More of them are surviving, so more, they have the mating genes, so they're reproducing more, similar to that and, ..

P3(f): Yeap, yeah.

P12(f): It's not that they're working out everyday.
P3(f): No [both laugh]

P12(f): Pumping iron.

P3(f): So, would you say we answered part 'a'?

P12(f): Uh hmm.

P3(f): That they're better adapted to survive in that environment.

P12(f): Better adapted?

P3(f): They're better adapted to that environment.

P12(f): They're not actually adapting.

P3(f): No, I didn't say adapting. Adapted, because they have the favourable combination of genes that helps them to survive.

P12(f): In that particular environment.

P3(f): In that particular environment.

P12(f): If they were in another environment, they may not do the same.

P3(f): That's right, that's right.

P12(f): The environment is selecting who survives in the end.

P3(f): That's right.

P12(f): OK.

As with question five, despite the fact that participants were examining gene graphs, there was a strong tendency on the part of some groups to slip away from the gene-level view and into the individual level perspective of selection. The following dialogue illustrates not only the tendency to see individual ants (i.e., “they”) as the target of selection, but it also reveals a “fit is bravado” sentiment as well.

Group H

P5(h): [Begins reading question 6 out loud]. Survival of the fittest means that those who are able to take care of themselves and fend for themselves and ...
P19(h): Yeah, even within the red population we have, we see 7 and they are so old. Like, they're, they can adapt to the environment so well, so that they weren't killed, they remain. They survived.

P5(h): Right, right. They just weren't able to mate.

P19(h): Yes. So, within the red population they're the fittest, that's why they survived.

P5(h): Well, go to the strength one again. Survival of the fittest are the strongest, remember? Go to the strength one again.

P19(h): 11?

P5(h): The strongest were the most prosperous.

P19(h): Yeah.

P5(h): So strong, strong being you know, ah, a term used equivalently to, to being fit, right?

The next dialogue illustrates just how easy it is to lose track of exactly what the focus should be when discussing fitness. P11 starts out with an excellent definition for “survival of the fittest” by concentrating on a gene-level view of selection. However, near the end of the exchange, P10 suggested a species-level view of selection and P11 acquiesces to this view. Thus, this exchange fell into the mixed category. That is, the group entertains several perspectives on the target of selection simultaneously while examining the gene graphs. Near the end, P11 indicated that populations are now the focus of the discussion. It is encouraging that P11 ended the exchange by noting the importance of gene-gene interactions in understanding fitness.

Group D
P11(d): OK, so, attacks only black, only red, um. Survival of the fittest means, .., please explain your answer. Well this particular graph, we have the red ants who attack only the black ants surviving.

P10(d): Uh hmm

P11(d): And, the ..,

P10(d): Survival of the fittest ..,

P11(d): Well, survival of the fittest basically has to do with, .., if you pass, if you're able to pass on your genes or not. So, if you survive long enough
to do so. Now, if you're an ant that's killing off your own, like you're killing off your own, like you're killing off other red ants, then you're not really promoting the um, ..., you're not promoting, the survival of your species. OK? So ...

P10(d): But not every red ant have [sic] the same genes, right?

P11(d): No. I mean if you're killing off other red ants, who are you going to mate with? Right?

P10(d): OK, the black ants are killed, the red ants only, then increase and then decrease again.

P11(d): Uh hmm. I think red ants just have a better combination of genes altogether, that help them to survive overall. This is a difficult graph, too. But, I think the fittest in this case that only kill the black ants.

P10(d): Right, they kill others, then they promote the survival of their own species.

P11(d): That's right because they're increasing um, ..., But see all the other populations are going down as well and they're the ones that are ..., Well, ..., I wonder if they, ..., It's so hard to look at individual ..., I'm going to change, look at a different graph. It's so hard to look at ..., different sharing genes. If you look at an individual gene in isolation it's really difficult I think.

The last category to emerge from the discussions regarding “survival of the fittest” was the idea that “strong” is synonymous with “fit”. That is, participants held the view that bravado was what mattered in an ant's (or its genes') struggle for survival. It was surprising that five of the eight groups demonstrated responses of this type. The dialogue below also exemplifies how tempting and easy it is to use the non-technical vernacular when a more reasoned answer was being solicited. This example, taken from group G, is typical of the bravado category.

*Group G*

P16(g): Survival to the fittest means ..., .

P18(g): The ones with the most favourable characteristics will ..., .

P16(g): Just, the strong survive.

P18(g): The strong survive, yeah. Um, ..., .
Despite some apparent misconceptions in part 'A', part 'B' of question six generated some remarkable discussions that revealed how beneficial the simulation could be in helping most (but not all) participants formulate and examine their conceptions of fitness. The responses for part 'B' were categorized according to whether participants answered the question with either a 'no' or a 'yes'. Two groups (A, G) answered 'no' and the remaining six groups (B, C, D, E, F, H) answered 'yes'. It is important to note that there is no right or wrong answer to this question. Each group could arrive at different conclusions and still be correct since there were many aspects of the simulation's environmental parameters (e.g., food being placed randomly in the environment, the anteater appearing at random locations and at random intervals) that would allow for completely different phenotypes to evolve. What matters for this analysis is how the group members qualified their answers. Because these dialogues were so illustrative of the ways in which the simulation facilitated concept exploration and attainment, an exchange from each of the eight groups will be presented and discussed.

Group A's conception of fitness was consistent with the idea that evolutionary fitness means, for example, being the strongest, moving the fastest, seeing the farthest, and being the bravest. P8's reference to "pretty major things" near the end of this dialogue indicates that fitness is not relative to the environment in which certain phenotypes are expressed but is to be weighed against some type of absolute scale (e.g., strongest is best). Unfortunately, all three group members appeared to agree with this general sentiment.

**Group A**
P8(a): So, when you put weak, cowardly, and lazy, or ... strength zero, attack 0, and movement zero, could it still be fit?

P7(a): See, we don't have an output of a graph of that population that has all those. What we'd need is all those numbers.

P4(a): Yeah, yeah.

P8(a): And if for movement they can't get food, ...

P7(a): Yeah.

P8(a): They can't run away from the anteater. So, how can they survive enough to reproduce?
P7(a): Yeah, that's what I'm thinking. So, there's a big difference between here, or here which is like 3% vs. 70%, right?

P4(a): Yeah.

P8(a): And if they can't move and someone comes and takes whatever food they have, they have no strength to fight back.

P7(a): So, what was this question? Did we answer this?

P8(a): Yeap. Could it still be fit?

P7(a): No.

P8(a): We would say no. Because those are pretty major things.

P7(a): Yeah, and it wouldn't survive.

Group G also answered 'no' to part 'B' of question six. This group, like group A, does not explicitly mention the role of the current environment in their assessment of the question. They do, however, acknowledge that it might be possible for some combination of weak, cowardly, and lazy phenotypes to exist. They go on to reject this possibility because they can find no evidence for it in the gene graphs. In other words, group G was thinking about this combination of phenotypes in the context of the current environment and, as such, concluded that the "combination of being weak, cowardly and lazy is probably a bad combination." What matters, is that the simulation has raised the possibility that fitness is not a uni-dimensional construct and that it is closely interrelated with the environment.

Group G
P18(g): Ok. Part 'b'. Could an ant be weak, cowardly and lazy and still be fit? Well, we saw that a cowardly ant, one that never attacks will still survive because that's what the graph said and so we kind of thought that was because ..., maybe they avoid fights so they're not, they don't have the opportunity to get into fights because they don't enter into them, so they don't die that way.

P16(g): K.

P18(g): Could an ant be weak and still be fit? Well, let's look at the strength gene.

P16(g): Well, you gotta ..., it has to be all 3 at the same time.
P18(g): Oh, does it?

P16(g): Weak, cowardly and lazy and still be fit. So, is that the strength?

P18(g): This is the ah .., . strength gene, yeah. So, I guess the 4 is like the strongest gene? The cyan colour [line on the graph]

P16(g): Uh huh. Well, 1 represents the weakest, so ..

P18(g): Um, so, here the ants that have the best chance of surviving according to this graph, in reference to the strength gene, is the one with strength 2. So, that's not that strong. But he's still doing ok. And .., the ants with strength 1 are doing better than the ants with strength 3. So, they could be still considered fit.

P16(g): The guys with strength 4, it is doing better than um, .., well, consider about the same.

P18(g): Yeah, the guys with strength 4 and the guys with strength 1 are doing about the same, which is puzzling.

P16(g): Yeah. Or maybe the guys with strength 4, probably attack more.

P18(g): Yeah. So, then their survival could be balanced out by the fact that they get into more fights.

P16(g): Or, if they're stronger, they'll attack, they'll win, so survive.

P18(g): Yeah, ok. So, let's just look at the lazy graph. The ones that don't move at all are not good. They won't last very long cause no one's going to come give them food. So, the combination of being weak, cowardly and lazy is probably a bad combination. I don't know if you can say they can still be fit. But, on the other hand, just being weak and cowardly, an ant could be, you could do ok if you're an ant and weak and cowardly. You're not necessarily going to die out.

P16(g): Ok.

P18(g): Do you concur?

P16(g): I concur.

The remaining six dialogues are examples from groups who answered part 'B' with a 'yes' response. The brief exchange by group B is included because the comprehensive definition they gave for fitness (noted above) provided them the latitude to express their conclusion with confidence.
**Group B**
P6(b): Alright. So, what's part B?

P9(b): Could an ant be weak (strength = 1), cowardly and lazy and still be fit? Please explain your answer.

P6(b): Well, in that case, yeah. If they're sharing, then they're being helped.

P15(b): Yeah.

P9(b): That's right.

P6(b): And we just saw that in our graphs. Wonderful girls. That was absolutely well answered.

P15(b): We just proved that even before ...

P6(b): We just proved it.

P15(b): We knew that even before we look at the answer.

P6(b): I know.

P15(b): Lovely.

Of all the group dialogues presented for part 'B', this next discussion by group C is the most noteworthy for several reasons. First, the conversation is animated and dynamic. All members of the group are engrossed in the discussion and each participant appeared genuinely to be working towards finding an answer. Second, the group makes use of the graphs in trying to establish a conclusion. In other words, they sought evidence from the graphs throughout their dialogue to support their claims. Third, and this was quite unexpected, the group discovers (without realizing it) a rather esoteric but important evolutionary concept known as “the rare enemy effect” (Dawkins, 1982). The anteater is the “rare enemy” and this group has noticed, by examining the graphs, that there does not appear to be a strong selection pressure against ants which do not possess the “avoid anteater” gene. Although the group is unable to develop the idea fully, they at least speculate about how such an effect could arise and have provided a wonderful opportunity for a “teachable moment”. Last, although it takes them some time to reach a conclusion, they arrive at a reasonably accurate and robust conception of fitness.
Group C
P13(c): But anyways, yeah, I think it has to, for example, if we look at um, avoid anteater, which one is that, number 8?

P14(c): 9.

P13(c): Avoid anteater .., So .., which one is that?

P14(c): Is that 8 or 9?

P13(c): This is 8, for avoidance, percentage of surviving... is it 9?

P1(c): 9, yeah.

P13(c): Nine is avoid anteater genes. "Seeing-other-ant-genes" would be 9. We did this right? So, yes, is for white. Yes, means, yes it avoids?

P14(c): Yeah.

P13(c): No, means, no it doesn't avoid? Hello. Real good. So, if it avoids, it's .. what does it mean?

P14(c): It's avoiding, it survives.

P13(c): But, it's avoiding but it's not surviving but how come?

P1(c): Yeah, how come?

P14(c): This graph is alive, right. Alive ants.

P13(c): Yeah, so ..,

P14(c): So, they can't have no ..,

P13(c): This is weird.

P1(c): But then this is saying that only 20 percent of the ants are alive, versus, if they don't, I mean if they do have the ant[eater] avoidance gene, whereas .., there's a higher percentage that survived if they don't have it.

P13(c): You see if they don't have, you see no avoidance and they're still higher than the avoid, the ant with avoidance?

P1(c): So, in that particular case, the ones, the genes with um, ant avoidance are not selected for and like you were saying, it's, if it wasn't useful, ..,

P13(c): Yeah.
P1(c): So maybe it's not useful. Although, I can't image why it wouldn't be useful.

P13(c): I, this is weird. It's getting weird. I don't know, maybe this, this gene is not selected? Can you say that? Or maybe because there was only one anteater, right so. There was only one anteater ..,

P1(c): But how could it hurt?

P14(c): How do we know there is only one, like?

P13(c): I only saw one.

P14(c): It does it randomly. Sometimes it doesn't appear.

P13(c): OK, maybe this graph is not .., Why don't we look at attacking genes, or strength genes. Let's look at that. Maybe that would explain it. Ok, this, you see, for this one, Ok, this is the strength, like 1, is having low strength, 2 having you know, 4 having higher strength.

P1(c): Seems like red ants, need the strength, or

P14(c): They're weaker.

P1(c): Well, they, yeah, the weaker,

P13(c): The ants that have weaker strength are surviving then.

P14(c): [Begins to read part 'b' of a question]

P13(c): Could an ant be .., [reads part 'b' of the question]. Yes! This is the answer! Because ..,

P1(c): Yes it can, and that's what we're talking about people's perception of the word fit does not necessarily mean strength.

P13(c): Means, strength.

P1(c): It doesn't mean strength, necessarily.

P13(c): Even if it is weak and ..,

P14(c): This is good. We can use it for our lesson plan because we were arguing about it, not arguing but discussing about it.

P13(c): Yeah, this is what we were saying. So, strength, even though you see for the black ones, it's important to have that strength, ..,
P1(c): So, the red ones must be using something else to survive besides their strength.

P14(c): Yeah.

P13(c): But for this guy, even though they're cowardly and weak, they're still, you know, fittest.

P1(c): What was the original question we were answering?

P14(c): No, we finished.

P1(c): Oh, we finished? Ok.

P13(c): That's interesting. That's interesting. I think we're done survival of the fittest.

Group D provided the most clearly articulated answer for part 'B'. P11 expressed the idea that genes, and the environment in which they exist, are inextricably interdependent; fitness is a function of genes and environment. What is unique about this exchange is P11's speculations about what the environment would have to be like to support the conclusion she has offered. Unfortunately, the notion that these ideas could be tested simply by setting the environmental parameters in the simulation to the specifications suggested, was not expressed.

Group D
P11(d): Yeah, because they're reproducing while these ones are not. And so, they're, they're putting out more of their genes out into the population. So, they're fitter, in that sense. Ok. Ok, .. [Begins reading part 'b']. Well, let's look at the weak. Strength, is what, 1? Strength, so a weak one .., Which is 1. If they're weak, no, they're right down there.

P10(d): They're not fit.

P11(d): If they're cowardly, they never attack. So, which one was attack?

P10(d): 8, number 8. No, it's not number 8.

P11(d): Attacks, never attacks. No, it's low. I just, I don't think so. [Re-reads the question]. Well, depends on the environment.

P10(d): Weak, [Begins to reread the question].

P11(d): I mean, it depends on the environment. If you were living in an environment where your food is very light, you don't have lots of, you
know, there, it's not a very populated area, you don't have lots of neighbours and there's lots of food around. You don't have to travel very far to eat your food, then, yeah, then, it could, an ant could be very fit because it doesn't have to compete with other ants that have all these other um, um, traits. And also, this ant doesn't have to put the energy into those other traits, as well. So, they're expending less energy and therefore they would still be fit. That's my answer. I don't. What do you think, P10?

P10(d): Fit. Um, ..., K, if fit means the rate of survival, they can be yeah. Depends on the environment. If the environment, like they have a lot of predators and no food, if they don't move, they won't survive, right?

P11(d): Yeah, exactly.

P10(d): And then, they will not be able to transmit their genes to the next generation.

P11(d): Exactly.


P11(d): So, it depends on the environment then. Are we finished? We're finished.

Group E has also come to a well developed conclusion for part 'B' of the sixth question (see Table 9, p. 66). Group E notes that there is no evidence that, in the current environment, having the weak, lazy, cowardly phenotype appears to be fit. However, they acknowledge that in other environmental circumstances, this phenotype could prosper. Unlike, group D, this group does not speculate about the nature of such an environment.

Group E
P2(e): [Begins to read part 'b' of the question].

P17(e): I think yes.

P2(e): Well, let's see.

P17(e): Because fit is about, you being able to pass your genes to the next one, and if those characteristics, actually allow you to do that, then you ..,

P2(e): K, what? Cowardly?

P17(e): If they're cowardly, it means they won't attack, they avoid. So, it doesn't matter whether they're weak or strong.
P2(e): Now, would lazy hurt them? The ant doesn't move unless it sees food. Yeah, yeah. 'Cause survival of the fittest is you know, if it yeah, if it's able to pass on its gene. So, if this particular ant is suited to the environment that it's in, then, it may be the fit one in the environment, but if it's in an environment, if the parameters are such that it won't survive, then no. But yes, it can be fit. It can be fit, it can if the parameters are correct, and pass on its genes.

P17(e): Yeap, I think it's possible. Yeah.

P2(e): Yeah, because yeah, it makes sense. I mean, this will, but this will depend on the parameter, do you agree that this will depend on the, ..., whether, weak, cowardly, and lazy is fit, is advantageous, will depend on the parameters? Does that make sense? The environmental parameters? Alright good.

The next piece of dialogue is long but is important to include because it also illustrates that these two participants were able to take the data presented in the gene graphs and generate a well articulated and accurate answer regarding the concept of fitness. Moreover, they come to an almost identical conclusion to that reached by group E. They find that there was no evidence that having the weak, lazy, cowardly phenotype was fit in the current environment. However, they acknowledge that in other environmental circumstances this phenotype could prosper. In other words, they have discovered the intimate interrelationship between genotypes, phenotypes and the environment. Like group D, towards the end of the discussion, they speculate about what type of environment might allow the weak, lazy, cowardly phenotype to succeed.

Group F

P3(f): Part 'b' [reads the question]


P3(f): Weak, cowardly, and lazy.

P12(f): It's really not healthy. Well, if that's what the environment ..,

P3(f): And still be fit. Now, it depends on what you're definition of fit is.

P12(f): Well
P3(f): Like, what exactly does that mean?

P12(f): See, what I think they're trying to get at here is do we think survival of the fittest means you must be strong?

P3(f): Ah, ok. Right, right.

P12(f): Aggressive, ... So, what I'm saying is, sure they could still be fit ...

P3(f): Yeah, they can.

P12(f): According, like looking at survival of the fittest, if that's what the environment selects, if weaker ants, maybe the ..,

P3(f): But the environment wouldn't select that, though.

P12(f): Maybe the environment ..,

P3(f): 'Cause obviously, if they were all of this, right ..., If it gets attacked by another ant, or something, it's not going to know what to do. It won't have the strength to fight it.

P12(f): And it won't beat it.

P3(f): And it won't move around, so it won't be around so it won't eat food. So, it's going to die anyway. So, therefore how could it be fit to last in that environment? It'll just be slowly committing suicide, basically.

P12(f): I think there's two ways to look at this answer. One is, um, just looking in general, like if I said before, if this is what the environment, if these were the characteristics that, you know what I mean?

P3(f): Ok, if they were being selected for, yeah, ok.

P12(f): If the environment, to live, the environment. But when we look at this and think of it ..,

P3(f): Yeah,

P12(f): Logically, no. This ...

P3(f): Not, for this environment.

P12(f): This organism would not survive.

P3(f): No, not for the environment we've been given to work with. No, they're not fit for that environment.

P12(f): No.
P3(f): But these characteristics could enable them to help survive.

P12(f): In another environment.

P3(f): In another environment.

P12(f): But I have no idea what type of environment.

P3(f): Well, maybe ..

P12(f): Maybe in a hibernation environment.

P3(f): Yeah, or in an environment where they didn't have any natural enemies like an anteater moving through.

P12(f): Exactly.

P3(f): Where they didn't have another population of ants, that's eating food, and whatever.

P12(f): There's always lots of food.

P3(f): Yeah.

P12(f): Or, food's brought to them.

P3(f): 'Cause these ants are all sharing the same environment, right whether they're black or whether they're red, right.

P12(f): So, we should say, then, based on what we just said, they could still be fit. It just depends on the environment.

P3(f): Depends on the environment. But ..,

P12(f): Do, you agree with that?

P3(f): Yes, but given our environment that we were given ..,

P12(f): No.

P3(f): No, they're not fit.

P12(f): For that environment.

P3(f): For that environment. Ok.

P12(f): For another, perhaps.
P3(f): Right, ok.

P12(f): Alright.

Group H's exchange shows that their reliance on the simulation data allowed them to be guided towards a reasonably accurate conclusion about fitness despite the fact that there is some consternation that graph 11 reveals “weaker” ants could be more successful than “stronger” ants. The surprise is equally great when they discover that ants who never attack were also relatively more successful than their “combative” counterparts. In the end, P5's conclusion “... I suppose, as long as you get your genes passed on that's the main ..., the main thing” would make any biologist smile.

**Group H**

P5(h): [Begins reading part 'b' of the question]

P19(h): [Reads part 'b' out loud]. Wow, so we have to pick a weak one. Ah, strength, 11. Ok, so. ..

P5(h): 1, yeap. Well, saying it can have all those traits?

P19(h): Oh, yeah. We see it in black. So, they're weak but then they still remain a high percentage of the population.

P5(h): Right, they do. They're high.

P19(h): So, ah, according to graph 11, yes. They can still be fit so ..,

P5(h): [Reads question again]. So, go to attacks.

P19(h): Huh?

P5(h): Go to attacks.

P19(h): What do you mean, attacks?

P5(h): Attacks. Like, go to attacking genes, 10. Right, it's saying never attacks. Wow!

P19(h): Oh, yeah.

P5(h): They did the best.

P19(h): Oh, wow! So, it proves it that ..., What does “both” [an ant attacks both black and red ants]?
P5(h): Both. I don't know, what is it?
P19(h): Oh, so these ones never attack others, and these ones ..,
P5(h): Only attack red, and only attack black, and these ones attack both.
P19(h): This is really the opposite eh?
P5(h): You got it.
P19(h): If you don't ..,
P5(h): Doesn't mean they were strong, it just means they attacked.
P19(h): Yeah. So, if the ..,
P5(h): So, they obviously .., K, go to movement again. K, go back one more and to the movement one.
P19(h): 4?
P5(h): They still survived. So, I guess as long as you have the ability to pass your genes on, regardless of what, the way you are ..,
P19(h): Yeah, you probably can still ..
P5(h): Then I assume you can still be fit. Like, I suppose, as long as you get your genes passed on that's the main .., the main thing.
P19(h): Yeah.
P5(h): Right?
P19(h): Yeah, or the main, the mating I guess is the main factor then.
P5(h): I guess.
P19(h): If you can survive enough to mate ..,
P5(h): Survive long enough to mate then that's all that really matters.

Supplemental Findings
In this sub-section, two supplemental findings will be examined. First, quantitative findings that provide some insight into the dynamics of how the groups operated as a function of the members' EKS scores will be presented. This analysis was conducted because it became apparent that as the dialogues were being transcribed,
certain group members appeared to control and monopolize the discussions. Thus, an analysis was conducted to explore the dimensions of this observation more thoroughly. Second, a qualitative example of a direct link between a discussion about the simulation data and concept attainment will be examined. This piece of dialogue will be presented because it exemplifies the potential that a computer simulation can have for concept attainment.

Table 20 lists the average number of words uttered by each participant in phase four for all six questions combined. The mean was calculated as a function of their group membership and EKS score. Those groups that had participants with EKS scores from the same third of the distribution (i.e., groups C, G, H) have their individual EKS scores listed in the notes below the table. The data in Table 20 are noteworthy for two reasons. First, compared to participants with EKS scores in the upper third of the distribution, there was a tendency for those with relatively lower EKS scores to do more talking (see bold numbers in Table 20). This pattern was true for all three triads (i.e., groups A, B, C) and for three of the five dyads (i.e., groups E, G, H).

Table 20.
The average number of words uttered by each participant for all six questions combined as a function of group size (dyad/triad) and EKS distribution score (bottom, middle, and upper third).

<table>
<thead>
<tr>
<th>Group</th>
<th>B</th>
<th>M</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(triad)</td>
<td>12.9</td>
<td>5.8</td>
<td>9.6</td>
</tr>
<tr>
<td>B(triad)</td>
<td>12.5</td>
<td>7.1</td>
<td>12.2</td>
</tr>
<tr>
<td>C(triad)*</td>
<td>7.2 (P14)</td>
<td>-</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td>18.4 (P13)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D(dyad)</td>
<td>8.8</td>
<td>-</td>
<td>26.9</td>
</tr>
<tr>
<td>E(dyad)</td>
<td>21.9</td>
<td>-</td>
<td>10.0</td>
</tr>
<tr>
<td>F(dyad)</td>
<td>10.7</td>
<td>12.3</td>
<td>-</td>
</tr>
<tr>
<td>G(dyad)b</td>
<td>-</td>
<td>27.9 (P18)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.5 (P16)</td>
<td></td>
</tr>
<tr>
<td>H(dyad)c</td>
<td>-</td>
<td>12.1 (P5)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.8 (P19)</td>
<td></td>
</tr>
</tbody>
</table>

Notes:  
a - EKS: P14 = 2, P13 = 5  
b - EKS: P18 = 8, P16 = 10  
c - EKS: P5 = 8, P19 = 9

Exceptions to this pattern were noted for groups D and F. Group D was unique because one of the group members (P11) was the study's most knowledgeable participant. She consistently provided superior answers to all questions asked in phase four.
Consequently, many of her answers required protracted responses. Often her partner's (P10) role, in many of these exchanges, was one of probing P11 by asking her additional questions or by simply agreeing with what P11 had said. Group F was notable for the egalitarian nature of their exchanges. Both participants were conscious of allowing the other to articulate their answers without interrupting, and both ask probing questions with approximately the same frequency.

Second, and this trend in the data pertains only to the triads, there was a tendency for the exchanges to "isolate" one member of the group. In other words, one member in each of the triads spoke noticeably less than the other two members. In groups A and B, it was the individual from the middle of the EKS distribution who spoke less. In group C the participant who had the lowest score on the EKS contributed the least to the discussion. Possible explanations for why this pattern emerged among the triads will be discussed in Chapter 8.

The other supplemental finding to be discussed involves an exchange between P11 and P10 (group D). What transpires in the discussion results in an insight for P10. Importantly, P10's insight then appears in her subsequent concept map (see Figure 4, p. 156). Thus, despite P10's background knowledge of biology (i.e., 3 full-time undergraduate courses), natural selection is, apparently for the first time, seen as the process by which evolutionary change occurs.

**Group D**
P10(d): Do you think that is natural selection? I don't know.

P11(d): Well, I think it can be. I don't think natural selection has to occur you know, hundreds and hundreds of generations. It occurs at each generation and the actual results may not be superly dramatic and they're amplified by generations but it occurs at each generation. Natural selection occurs during each generation ..., I think.

P10(d): Ooooh, I realize something. I think natural selection is a process but like evolution will occur over a long time, right?

P11(d): Right. Exactly. Exactly, like it says, evolution by natural selection. See natural selection is occurring ...

P10(d): Natural selection is only a process, right?

P11(d): That's right. It's the process by which evolution occurs. Through which evolution occurs.
P10(d): But evolution won't occur in only 2 or 3 generations, right? It's natural selection, that's the process that brings evolution, right?

P11(d): Yeah, it can, it'll depend on how quickly your generations move.

P10(d): Right.

P11(d): Right, because if you have um, you know populations of bacteria, they produce so quickly, you can get evolution occurring very fast. So, it doesn't have to take a long time. It can...

P10(d): Right, good. Let's go to the next one.

As noted above, there is an attempt by P10 to incorporate this insight into her global framework of knowledge about evolutionary concepts (Figure 4).

Figure 4.
A concept map created by P10 showing her perceptions of the relevance of natural selection in evolution.

Summary
In summary, in this section sub-goal three which was to analyze and interpret the small-group discussions as group members interacted with the simulation, was examined. Also, research question four (Would using a computer simulation of basic evolutionary processes in combination with small-group discussion be an effective way to reveal the
nature of Intermediate/Senior pre-service science teachers' conceptions of evolution?) was answered.

First, the analyses of participants' dialogues as they used the simulation revealed a number of findings. Overall, participants found the simulation engaging, fun and relatively easy to use. Importantly, as participants interacted with the simulation, they were able to observe, comment, speculate, and hypothesize about the objects and events on the screen. In other words, the simulation created situations that participants felt compelled to explore and explain.

Second, participants were asked various questions about specific evolutionary concepts and asked to use the simulation data (gene graphs) to support their answers. Overall, there was a great deal of variability in the time devoted to answering the questions and in the depth of their responses. All groups were able to make specific and direct reference to the simulation data and to integrate them into their answers. Participants' discussions revealed that the gene graphs were relatively easy to read. Although, at times, most groups found it challenging to construct meaningful interpretations of the graphs with respect to the question being answered. Participants would sometimes find the gene graphs "weird", "strange" or "wrong" as they struggled to reconcile their own conceptual understanding of a concept with the data produced by the simulation.

Third, participants' answers to questions about the simulation revealed a wide array of strengths and weakness, between and within individuals, regarding their understanding of basic evolutionary concepts. Participants' ideas related to randomness, causal mechanisms of evolution, adaptations, natural selection, and fitness were explored. Not surprisingly, consistent patterns of responses emerged between questions because of the interrelated nature of the questions. Table 21 summarizes the themes that emerged from participants' discussions for each of the questions asked during phase two and four.

Expectedly, consistent themes arose with respect to targets of selection, gene-environment interaction, and conceptions of fitness. Moreover, the ways in which evolutionary terms, language, and phrases were used by participants were similar throughout the dialogues. Overall, participants' discussions of the simulation data showed, that while many may hold misconceptions (some seemingly intractable), their perspectives could be shifted and swayed by the evidence if it was discussed in the context of accurate prior knowledge held by at least one group member.
Table 21
The themes that emerged from participants' discussions about the simulation and questions answered during phase two and phase four.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Activity or Question</th>
<th>Emergent Themes in Dialogues</th>
</tr>
</thead>
</table>
| 2     | Using the simulation | - Task-oriented nature of running the program  
- Observations about the objects and events  
- Actions of the objects and events evoked excitement, curiosity and surprise  
- Ad hoc speculation and hypothesizing arose in attempts to account for the simulation events and objects  
- Anthropomorphic comments and responses were ubiquitous  
- Fascination with death, dying or killing |
|       | How do participants interpret the term "selection"? | - Tendency for participants to acquiesce to other group members  
- Discussions of content were descriptive and rarely explanatory |
| 1)    | Does randomness have a role in evolution? | - Non-interaction (randomness had no connection to evolutionary outcomes in the given environment)  
- Interaction (interrelated connection between random events and evolutionary outcomes) |
| 2)    | How does randomness affect evolution? | - General confusion regarding the concept of randomness per se |
| 3)    | How do participants interpret the word "need"? | - Question failed to elicit ideas about alternative interpretations for the word "need"  
- Gene combinations were considered important by some participants |
| 4)    | How do participants interpret "adapt" and "adapting"? | - Confated (the words were used interchangeably, no distinction in meaning was made)  
- Not conflated (a distinct separation in the meanings of the terms was made)  
- Lamarckian (the words were used to convey a Lamarckian conception of evolution) |
| 5)    | How do participants interpret the concept of natural selection? | - Gene (gene-level view of selection was espoused)  
- Individual (organism-level view of selection was articulated)  
- Mixed (any higher-level biological entity other than the gene; individual, population, species) |
| 6)    | How do participants interpret the term "fitness"? | - Gene (gene-level view of selection was espoused)  
- Individual (organism-level view of selection was adopted)  
- Mixed (any higher-level biological entity other than the gene; individual, population, species)  
- Bravado (fitness was seen as "strongest", "fastest", " bravest") |

Last, groups were arranged deliberately so that members differed in their level of understanding of evolutionary concepts. This created several dynamics in the kinds of exchanges that took place between group members. At times, the less knowledgeable participants appeared to advance their understanding of the concepts as a result of the exchanges with the more knowledgeable partners. At other times, it created discussions where the high or low knowledge group member(s) would passively agree with
statements uttered by their partners. These statements were sometimes challenged, ignored, or accepted. Lively debates would occur as each group member sought to explain events in the context of their own understanding and the data produced by the simulation. All of these scenarios could be entirely independent of whether an individual's actual utterances were accurate, meaningful or otherwise. Thus, despite the simulation's lack of visual sophistication, it served as the focal point for generating a rich and detailed picture of participants' understanding of basic evolutionary concepts.
Chapter 6
Results: Analyses of Participants' Understanding of Evolution

Today, almost half a century after the publication of the Encyclical [Humani generis, 1950], new knowledge has led to the recognition that the theory of evolution is more than a hypothesis. It is noteworthy that the theory of evolution has progressively taken root in the minds of researchers following a series of discoveries in different disciplines. The convergence, neither sought nor provoked, of results of studies undertaken independently from each other in itself constitutes a significant argument in favour of the theory (Pope John Paul II, 1996).

Lesson Plans

The results in this section address sub-goal number four, which was to explore the extent to which the standard practice of creating a lesson plan (i.e., on natural selection) could affect intermediate/senior pre-service science teachers’ conceptions of natural selection. This sub-goal was assessed by examining participants’ ideas related to natural selection in the lesson plan they submitted and the extent to which the lesson could realistically accomplish the objective of helping high school students understand this concept in a 70 minute period. The same group members who worked together while running the simulation also created the lesson plan together. Thus, a total of eight groups (three triads and five dyads) produced a lesson plan on natural selection.

The approaches that each group used to address the concept of natural selection in their lessons fell into one of three categories: 1) activity-based (5/8, 63%), 2) case study (2/8, 25%), and 3) mixed approach (activity and case study combined, 1/8, 12%). All of the lessons that included an activity-based approach used some variant of a game where students were supposed to act as the selection agent/pressure on a population of artificial organisms (e.g., coloured poker chips, pieces of wool) in an artificial environment (e.g., a 1 metre by 1 metre sheet of coloured paper, petri dishes). Students were then instructed to tally the number of organisms that “died” and “survived” through several iterations of the game, and were asked to graph the data and to discuss and explain any patterns that emerged. A good example of this approach can be found in “Teaching about Evolution and the Nature of Science” (National Academy of Sciences, 1998, Chapter six, Activity three). Conversely, all the lessons that included a case-study approach used the Peppered Moth example (e.g., see Ridley, 1996) or some other animal (e.g., wolves, insects, birds) to illustrate natural selection in real populations.
While all of the groups made an attempt to address natural selection in their lessons, they varied considerably in the quality of how the principle was “unpacked”. That is, the principle of natural selection involves several interrelated concepts that research has shown are typically difficult for students to understand (Bishop & Anderson, 1990; Brumby, 1984). Each of these concepts must be understood alone and in connection with the others before accurate conceptions of the mechanism can be expected. For example, one group provided no standardized definition for natural selection as a framework in their lesson. Instead, the expectation in this group's lesson was that the activity (a hands-on simulation of natural selection), and a discussion of its results among students would lead to the emergence of the principle of natural selection. It is noteworthy that this group had set aside a 10 minute time slot after the activity where students would “develop natural selection” from the data gathered during the simulation.

In contrast to this one group, the other seven groups (88%) provided a more formal definition of natural selection as the focal point of their lessons. The activities and/or case studies were used to illustrate the concepts inherent in the definition. Table 22 lists the definitions of natural selection (verbatim) that these seven groups used as the focal point for their lessons.

As Table 22 illustrates, not all of these definitions were accurate or even addressed the process per se. Moreover, many definitions contained words and phrases that themselves would require further “unpacking” if students were to gain any insight into their biological meaning. For example, the definition provided by group A is true but contains no information pertaining to any details of natural selection as the mechanism by which populations are “modified”. Also, there was nothing in Group A's lesson plan that specifically linked their activity to this definition. The definition provided by group B is inaccurate. Natural selection is not an “ability” of populations; it is the principle mechanism by which the genetic constitution of populations changes over time as a result of the non-random elimination of relatively less successful alleles. Furthermore, this group's lesson plan directed students to examine this definition (which was to be written on the board) and to put it “into their own words.” The definitions provided by groups C, E, and F make reference to “favoured” or “favourable” variations. However, only Group C provided explicit examples and links in their lesson of how such variations arose and specific examples of what was meant by “variations” and how they could lead to a population of organisms possessing adaptations for a given environment.
The definitions of natural selection provided by the groups who included one in their lesson plans.

<table>
<thead>
<tr>
<th>Group*</th>
<th>Definition of natural selection provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (n = 3)</td>
<td>Natural selection is the principal process by which populations have been modified in response to environmental changes.</td>
</tr>
<tr>
<td>B (n = 3)</td>
<td>Natural selection is the ability for a population to survive, adapt and reproduce in response to the environment.</td>
</tr>
</tbody>
</table>
| C (n = 3) | - a mechanism for a change in populations that occurs when organisms with favourable variations for a particular environment survive, reproduce and pass these variations on to the next generation.  
- those organisms with less favourable variations are less likely to survive and pass on traits.  
- therefore each new generation is made up largely of offspring from parents with the most favourable variation.  
- For Darwin, variations were essential to the natural selection process. |
| D (n = 2) | Natural selection is composed of two distinct concepts: 1) new traits (characteristics) come from seemingly random changes in genetic material such as mutations and genetic recombinations. 2) Since organisms have extremely high reproductive rates, slight genetic variations among individuals significantly affects an organism's chance of survival and reproduction. |
| E (n = 2) | - The preservation from generation to generation of favourable individual differences  
- Continuance of genes in successive generations caused by different degrees of adaptedness to the environment.  
- Survival of the fittest |
| F (n = 2) | - The differential survival or reproduction of favoured variants. And, given sufficient time, can gradually transform species and produce both detailed adaptation in single species and the large-scale, long-term improvement of types. |
| H (n = 2) | - Natural selection results in the best adapted organisms surviving and reproducing, thus passing on their genes to the next generation.  
- defined as the differential reproduction of alternative variants, determined by the fact that some variants increase the chances of survival and reproduction of their carriers relative to the carriers of the variant.  
- process of selection acts like a sieve. Variants that interfere with successful solutions to adaptive problems are filtered out. Variants that contribute to the successful solution of an adaptive problem pass through the selective sieve.  
- According to Charles Darwin, it is the survival of the fittest. “Fitness” in this sense did not mean muscular of the fastest runner. It simply meant the best able to survive and reproduce. |

* Note: Group G provided no definition of natural selection.

It must be noted that the definitions of natural selection cited by groups C, E, and F are commonly found in most high school texts and, unfortunately, they convey a subtle but misleading error regarding the causal chain of events that leads to the emergence of adaptations in a population. The problem is this: these definitions contain the notion that an adaptation is somehow “favourable” before it effects changes in an organism's genes' relative rate of survival and reproduction. However, the reverse is true. Human observers only know that a trait is “favourable” in a population of organisms after changes in relative rates of survival or reproduction have occurred. This error is most
evident in the first sentence of group H's definition of natural selection (see Table 22). It is those individuals in a population of organisms that are relatively more successful at surviving and reproducing that will, over evolutionary time, come to possess heritable traits (adaptations) that are, when viewed from the human point-of-view, matched exquisitely in form and function to the environment in which they exist. This point can be emphasized further with the simple evolutionary truism that what functions as an adaptation today may, literally, not be tomorrow. Note that the remainder of group H's definition is very clear and the sieve metaphor accurately portrays the bulk of the process of natural selection. Unfortunately, their lesson did not make any additional explicit use of the metaphor.

The definition provided by group D was the most promising of all stated. Biologists regard the process of natural selection as involving two distinct but interrelated processes. This group attempted to highlight these two events but the conceptualizations that resulted were not entirely clear. For example, part one of their definition accurately notes the random nature of mutations and recombination. But, the lesson appears to assume students understand the concept of randomness. Moreover, there was no expressed connection discussed in the lesson between the random changes that take place in a genotype and the effects these changes have on an organism's phenotype. Part two of Group D's definition conflates rate and capacity. Furthermore, this group fails to capitalize on an explicit statement of the second process involved in natural selection; the *nonrandom* elimination ("filtering") of individuals with relatively less successful phenotypes as they are manifested in a given environment.

There is one final point that should be noted about the lesson plans submitted by all of the groups. Given the complexities of the concepts involved in the principle of natural selection, all but the lessons submitted by groups B and C attempted to cover vastly more material than students could possibly be expected to understand in a single 70 minute period. For example, in addition to understanding the mechanism of natural selection, here are some other concepts that students were "expected to know" upon completion of the lesson: "Understand the relationship between predator and their prey in the natural environment" (group A); "Understand and use the Chi-squared test as a tool to test a hypothesis of an experiment" (group D); "Stabilizing, directional and divergent selection" (group E); "Understand and explain the terms adaptation, mutation, genes, evolution, natural selection, 'survival of the fittest' and artificial selection and to describe
the factors that affect natural selection.” (group F); “Understanding and interpreting a theory and developing a hypothesis based on observations and evidence” (group G); “Be able to relate the knowledge of evolution and natural selection to the many happenings of the world around us … and to know another scientist’s view of evolution” (group H).

In summary, the concept of natural selection in the lessons submitted by the eight groups of participants was addressed in a way that did not reveal many of the important features of the process. Moreover, all but two groups attempted to cover much more material than students at a grade 11 or 12 level could reasonably be expected to learn in a 70 minute lesson.

Concept Maps

Recall that in this phase of the study, participants were asked to create concept maps after they had run the simulation twice and had worked together in groups to create a lesson plan on natural selection. The concept maps were used as a means of exploring the nature and extent to which participants could connect the major components of evolution into a coherent framework of related ideas. Each map was evaluated by the author and an independent examiner (an expert on evolutionary psychology) as belonging to one of two broad categories: 1) Conceptually vague, and 2) Misconceptions. These two categories were relatively independent but there were instances of concept maps containing some overlap in content. The misconception category contained four overlapping subcategories: 1) Saltation, 2) Lamarckian, 3) Causal order, and 4) Level of selection.

Overall, 5 of the 19 participants' concept maps were categorized as conceptually vague and 14 of the 19 concept maps were categorized as containing misconceptions. One or more concept maps from each category or sub-category will be reproduced and discussed next. Where the quality of a concept map precluded accurate digitizing with the aid of a scanner, the map was reproduced as accurately as possible using a computer graphics drawing program.

The five concept maps that were categorized as conceptually vague had all of the requisite seed concepts (i.e., genes, population, environment, mutations, natural selection) present. However, the linking terms used to indicate the relationship between concepts were either absent or contained words or phrases that failed to convey the nature of association. Additionally, none of the maps in this category contained any explicit
indication of differential survival or reproduction. In short, these maps were correct but incomplete. Unfortunately, there was no way to judge, from the information provided on the map, the extent to which a participant held a conceptually accurate, coherent and integrated framework of major evolutionary ideas.

The first example of a concept map classified as being conceptually vague (Figure 5) was created by P13. This individual was in the LL groups (i.e., low EKS, low ITEQ) and reported taking a total of six full-year undergraduate biology courses. Her map does contain the five seed concepts asked for in the task. However, it does not contain any new concepts that were to be integrated with the original five seed concepts. Noticeably absent is any mention of how natural selection operates to ensure "favourable genes are selected by" the environment. Also, many of the linkage terms and phrases convey only cursory information about the nature of the relationship between concepts (e.g., Populations 'must have' Genes).

**Figure 5.**
A concept map categorized as "conceptually vague" created by P13.

Another example of a concept map (Figure 6) that fell into the conceptually vague category was created by P17. This individual was in the HH group (i.e., high EKS, high ITEQ) and reported taking at total of two full-year undergraduate biology courses. P17's map contains the five seed concepts and several additional concepts. The map is
comprehensive and includes several fundamental concepts that are arranged spatially into three relatively distinct areas. However, the map contains no linkage terms or phrases making it impossible to know how the participant thinks the concepts are related. For example, how should the relationships between “Natural Selection”, “Evolution”, and “Speciation and “Extinction” be interpreted? The foundation of Darwin's ideas depends on how these terms are related. Thus, despite instruction which asked participants to use linking words and phrases that conveyed the “essential nature of the relationship among concepts” this participant provided none.

Figure 6.
A concept map categorized as “conceptually vague” created by P17.
Under the broad theme of "misconceptions", it was surprising to find three out of the 19 participants created concept maps that fell into the sub-category of *saltation*. Saltation is the idea that gene mutations can, in a single generation, result in the appearance of a new, fully-functional adaptation or cause the appearance of new species. Concept maps that contained a saltation misconception had a link that indicated a direct connection between mutations and the appearance of a new species (see Figure 7).

**Figure 7.**
A concept map categorized as containing a "saltation" misconception created by P8.
This map was created by P8 who was in the LL group (i.e., low EKS, low ITEQ) and reported taking six full-time courses in undergraduate biology. The phrase used to connect “environment” and “natural selection” is interesting and suggests that this participant knows that the two are somehow related, but is unable to provide a coherent link between them.

Figure 8 is an example of a concept map that contained a *Lamarckian* misconception. Two of the 19 participants created concept maps with the idea that there is a “need” among populations or individuals to have adaptations for survival. Figure 8 was created by P9 who was in the HH group and reported taking 7.5 full-time undergraduate biology course.

**Figure 8.**
A concept map categorized as containing a “Lamarckian” misconception created by P9.

![Concept Map](image)

Specifically, P9 indicated in the lower right corner of the concept map that a “Population needs → Adaptations”. There is also a hint of this misconception in the linking phrase
"genes with adaptability" at the bottom of the map. This latter phrase suggests that genes can somehow control the direction they take in becoming successful as adaptations. This notion, known as "directed mutations", has not received support among members of the biological community.

There was a total of 3 of the 19 participants who had concept maps that were categorized as having causal order misconceptions. These maps were characterized by the idea that adaptations are being selected for. As noted earlier, this is a rather subtle error that is, in fact, the reverse of what transpires in nature. Specifically, phenotypic traits only become adaptations as a consequence of being relatively successful at helping those individuals in a population that possess them to survive and reproduce. What is currently an adaptation possessed by some individuals in a population can, in a single generation, become a trait that is maladaptive. The next map (Figure 9) contains an example of this error.

Figure 9.
A concept map categorized as containing a "causal order" misconception created by P1.
Figure 9 was created by P1, who was in the HH group and who reported taking five full-time undergraduate biology courses. Note that this concept map contains two examples of linking phrases that indicate this error; one in the centre of the map (i.e., genetic variation linking to adaptation) and one that links "adaptation" with "fitness".

The most common misconception observed in the concept maps was related to the category, "level of selection". Six out of the 19 participants created concept maps that contained misconceptions of this type. Concept maps that contained level of selection misconceptions were characterized by links that suggested entities other than genes were the targets of natural selection. Figure 10 is a concept map that contains links that indicated both the organism and the species are the targets upon which natural selection operates. This map was created by P6, who was in the LL group and reported taking 1.5 full-time undergraduate biology courses.

Figure 10.
A concept map categorized as containing a "level of selection" misconception created by P6.
Another example of a concept map that contains a *level of selection* misconception is presented in Figure 11. In the lower right corner of the concept map, there is a link suggesting that “survival of the fittest --- occurs on → individuals”. Additionally, the link between “natural selection” and “population” is not specific enough making it impossible to know what unit within the population (e.g., gene, individual), the participant believes is the target of selection.

**Figure 11.**
A concept map categorized as containing a “level of selection” misconception created by P2.
Another interesting aspect of this concept map is the dual linking of "mutations" and "genes". This map shows them inappropriately related through natural selection. This map was created by P2 who was in the LL group and reported taking 4.5 full-time undergraduate biology courses.

Applied Knowledge

To explore the nature and extent of any changes in participants' conceptions of basic evolutionary concepts after taking part in the first five phases of this study, all participants were asked to answer two questions during a structured final interview (Phase 6, see Table 6, p. 51). The two interview questions were as follows:

1) Cheetahs, (large African cats) are able to run faster than 100 km/hr when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 40 km/hr?

2) Cave salamanders are blind (they have eyes which are not functional). How would a biologist explain how blind cave salamanders evolved from sighted ancestors?

Participants' responses to the final interview questions were coded by the researcher and one independent examiner as being Darwinian, Lamarckian or Other in nature (Zuzovsky, 1994; Jensen & Finley, 1996). The coders agreed on which of the participants' responses belonged to a given category for 95% of the answers. Table 23 indicates the percentage of participants whose answers fell within each of the three categories for the two questions.

Table 23.

<table>
<thead>
<tr>
<th>Category</th>
<th>Question</th>
<th>Darwinian (n=19)</th>
<th>Lamarckian (n=4)</th>
<th>Other (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheetah</td>
<td>79 (n=15)</td>
<td>21 (n=4)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Salamander</td>
<td>5 (n=1)</td>
<td>74 (n=14)</td>
<td>21 (n=4)</td>
<td></td>
</tr>
</tbody>
</table>

That 79% of the participants could provide a Darwinian answer to the Cheetah question was encouraging. However, when the question involved a counter intuitive
example (i.e., the evolution of blindness in Salamanders), only one participant (5%) was able to provide a coherent Darwinian response. In order to give some sense of the kinds of responses participants provided for each category, an example or two will be presented along with a brief explanation.

Darwinian responses for the Cheetah and Salamander questions tended to include the ideas that there was a relative difference in survival as a function of differences in running ability and that this difference could be passed on to offspring. The heritable nature of the trait was sometimes explicit (e.g., Quotation 1) but, for most participants, it tended to be implicit. When participants did not include specific mention of random variability in running speed among cheetahs in their answer to the first interview question, participants were probed about the original source of differences in running speed. In total, 11 participants were probed but only four respondents were able to express the idea that differences in running speed among cheetahs arose by “chance” or were due to “randomness”.

Quotation 1: “So, back then, certain cheetahs could run faster, they're genetically predisposed to run faster at say 40 kilometers an hour compared to um, other cheetahs who weren't genetically predisposed to run as fast. So, those that could run at the 40 kilometers an hour survived and they passed their genes on to their offspring.” (P7)

Quotation 2 was the only Darwinian answer supplied for the Salamander question. This particular response is noteworthy because this participant also provided an equally coherent Darwinian response to the Cheetah question. In other words, this participant recognized that the basic evolutionary mechanism operating in both circumstances is identical; the species-specific details that lead to adaptive changes in the population are a secondary matter open to scientific investigation.

Quotation 2: “Um .. there's gonna be .. there's gonna be variability. There are going to be salamanders who are born with perhaps smaller eyes or eyes that do not use as much resources. And so, they could then use the left-over resources, say, for .. for um activities which would increase their fitness in terms of being able to breed and produce offspring and that character trait would then um ... aid them in terms of reproducing and breeding and the idea of having, or the character trait of smaller eyes would be the character trait that would be passed on to future generations because the individuals with say, smaller eyes or eyes which use up less
energy resources, would be the ones that would be surviving... Again, a long convoluted ... but ... with both examples, you still have the general trend of, there's variability in a population. One particular trait will render an individual more fit or will give them an advantage in terms of reproducing. And .. and so, they're [the two questions] not radically different, I don't think.” (P11)

Lamarckian responses to the Cheetah and Salamander questions tended to include the notion that there was an ability of the organism to effect changes in the trait (e.g., running speed) (e.g., Quotation 3). Typically, there was no mention of variability in the population, implying that all members were equally likely to survive (e.g., Quotation 4). Quotation 5 is a good example of a Lamarckian response that includes both the ideas of “needs of the organism” and the theory of “use and disuse”.

Quotation 3: “Well, if they're hunting prey that could move fast then certain organisms might develop the trait, the trait whatever that may be, to hunt these faster prey out. Like that's the most obvious thing that comes to mind.” (P16)

Quotation 4: “Because evolution takes a long time that's why their ancestors may run um, like slower, and then after a very long time the genes may change because they might experience some predators which runs faster than the cheetahs. So, after a long period of time they develop some genes, maybe a very long time, millions of years, and then they develop some genes which encourage them to run faster.” (P10)

Quotation 5: “Hmmm... Interesting. That's one of the ones I had problems with, with the whole webbed feet thing. Um, I guess they would explain it with the old, ah, cliché, you don't use it, you lose it type thing. So, I guess after years and years of not developing those muscles that were needed to be used for sight and eyes and all that other stuff, that they eventually just became obsolete.” (P5)

The “Other” category for responses to the Salamander question included a vague or descriptive answer that lacked any in-depth explanatory details (e.g., Quotation 6). No “Other” responses were noted for the Cheetah question.

Quotation 6: “What would be the advantage to that? Well, there had to have been some sort of advantage um ... to that unless it meant that the sighted salamanders may ..., may not have always lived in caves. They may have ..., there may have been a change in the environment or something that led to the non-seeing ones being able to compete better than the sighted ones ..., I guess. I have no idea.” (P15)
Resource Use

Participants' views on the simulation (see next section) were corroborated by examining their use of resources with Resource Use Survey (RUS, Appendix D) during the final interview (phase six). The RUS asked participants to use a checklist to rate those resources they had actually used and which they found most useful in helping them to understand evolutionary concepts. Six types of resources were available to participants during the various phases of the investigation. The six resources were divided into two broad categories: information resources and activity-based resources. The information resources included: 1) the readings (i.e., the chapter from Dennett (1995), readings from McComas (1994), and the handbook on evolution published by the National Academy of Sciences, 1998), 2) an Internet resource (http://www.oise.utoronto.ca/~rmacdonald/evolution), and 3) participants' own background knowledge on evolution. The activity-based resources were: 1) using the simulation, 2) working in groups (i.e., for the lesson plan and the simulation), and 3) creating the lesson plan.

Interesting patterns of reported usefulness emerged for both the information resources and the activity-based resources. With regard to the information resources, Table 24 lists which of the three information resources participants found most useful in helping them to understand evolutionary concepts as a function of their EKS category. First, all three resources were preferred about equally when a participant's EKS category was not considered. That is, among the 19 participants, the Internet resource was preferred most (37%), followed by the readings (32%) and personal knowledge (31%).

Table 24
Percentage of participants who ranked a given information resource most useful as a function of their EKS category (low - high).

<table>
<thead>
<tr>
<th>EKS category</th>
<th>Information Resource</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Personal knowledge</td>
</tr>
<tr>
<td>Low knowledge (n = 10)</td>
<td>5</td>
</tr>
<tr>
<td>High knowledge (n = 9)</td>
<td>26</td>
</tr>
</tbody>
</table>

However, when participants were grouped into an EKS category, there was a fairly distinct separation among those who relied on their personal knowledge compared to those who used the Internet resource. Specifically, 26% of the high knowledge subjects
reported that their own personal previous knowledge was the most useful information resource used in helping them to understand evolutionary concepts. Whereas, 32% of low knowledge subjects stated that the Internet resource was the most useful information resource used in the study.

An equally interesting pattern emerged among participants regarding the activity-based resources used in the study (Table 25). Overall, 47% of participants reported that the simulation was the most useful activity in helping them to understand evolutionary concepts, compared with either creating the lesson plan (37%) or working in groups

Table 25

<table>
<thead>
<tr>
<th>EKS category</th>
<th>Activity-based Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The Simulation</td>
</tr>
<tr>
<td>Low knowledge (n = 10)</td>
<td>26</td>
</tr>
<tr>
<td>High knowledge (n = 9)</td>
<td>21</td>
</tr>
</tbody>
</table>

(16%). These results must be qualified because using the simulation and creating the lesson plan were group activities. The distinction lies in separating the nature of the activity per se from the processes inherent in doing the activities. That is, it is reasonable to conclude that participants were able to separate the nature of the activity (e.g., using the simulation, creating a lesson plan) from the processes and interpersonal dynamics involved in how these activities were performed. In other words, a large majority of participants (84%) indicated that the dynamics of working in groups was not an activity they found useful in learning about evolutionary concepts. The relatively low value expressed by participants for the usefulness of working in groups by both low and high EKS groups was, as discussed below, a sentiment echoed strongly by some in the final interviews. Overall, unlike the pattern noted above for information resources, there was no clear differentiation between high and low EKS groups for how the activity-based resources were used.

Perspectives on the Simulation

Participants were also asked to respond to three semi-structured, open-ended questions about the simulation during the final interview. The final interview questions were: 1) “What did you think of the simulation?”, 2) “In what ways was the simulation
useful or helpful to you in understanding evolutionary concepts?”, and 3) “In what ways was the simulation confusing or not helpful to you in understanding evolutionary concepts?”. In total, four categories emerged from participants' responses: 1) Useful/Helpful, 2) Confusing/Not Helpful, 3) Prior Knowledge, and 4) Personal. The prior knowledge category was related to the participants' beliefs regarding the importance of users having some type of background knowledge or introduction to the simulation before using it. The fourth category, “Personal”, contained three responses that were significant because they captured unique individual ideas or stories.

Each of the four categories and their sub-categories will be discussed below, followed by one or two responses that are illustrative of each category. In some cases, several responses will be cited because of their significance to the overall goals of the study. Some participants provided more than one type of response. Unless otherwise noted, all quoted responses within a category were produced by different participants.

The “Useful/Helpful” category was made up of three sub-categories which contained responses related to: 1) the “Interface”, 2) “Group Work”, and 3) “Improved Conceptions”. The usefulness and simplicity of the program's interface was viewed by two respondents as a beneficial aspect of using the simulation. They felt that despite their limited computer background, the program was sufficiently easy and well structured to allow them to focus less on learning the program and more on learning about the concepts behind the program. That the program was reported to be simple to use was an important finding because a complex interface could have interfered with exploring the fundamental concepts. Here are two examples of what the participants stated about the interface:

I liked it. It was simple. I mean it was simple not only in the terms of, I mean in this day and age we are used to everything being so high tech and you'd expect these little like ant shapes and things like that but it was thought provoking because you looked at this and even though, you know, you weren't looking, you were more looking for the data that was produced. It wasn't actually just sitting down and watching the simulation occur. You know, you'd watch and say, “Oh, there's the anteater” or whatever… And different kinds of options were presented because of that, you were able to take a look at things from a different view. And, it was easy to use. I mean it was straightforward, everything was laid out, we went through it, you know, plug this, plug that in, you know, take a look at the data when you get into the, analyzing the data, you know, click here and do this. So in that case it was good because a lot of the trickier stuff was done for us and we went through it and were able to do it. And
concentrate, therefore, on analyzing it as opposed to running the program. Sometimes you spend so much time trying to get the thing running that you lose the whole purpose, which is to take a look at something (P2).

No, I think it [the simulation] was fairly straightforward itself. Some of, well, I guess this was just a personal preference. Some of it wasn't as interesting as others. So, I just kind of ignored that part and looked at the stuff that you were interested in (P18).

The other important aspect of the interface that was mentioned as useful by some participants was the graphs that were used to present the simulation data. Six participants stated that the information presented in the graphs was valuable in helping them to understand the data:

Well, it's nice. I liked the graphs. If I can at all ever change something written into a picture format, that's the way for me to do it. And I found the graphs really useful and I think that you can get a lot of information off of the graphs. And I think that part of the simulation was really helpful (P15).

The graphs afterward. Just comparing them and actually seeing the numbers when we were able to click back and actually see the numbers decrease or increase. That was .. that was good. And because we knew the traits of them, we knew those ones were surviving. We kind of pieced the things together and you could tell. That helped understanding it. For instance, on a graph, what would happen over a period of time and it made you think about .., you had to, again, because you were generating hypotheses, “what could be the possible options for that graph”, were generated and why did it end up having a dip at some point in time. Could it be that there was some environmental factors etc? (P8).

Five participants noted that the group work was a significant factor in helping them understand evolutionary concepts as they ran the simulation. This finding was important because participants were worked in groups based on the premise that some disparity in levels of knowledge about evolutionary concepts would help to generate discussion and could be of benefit to both the high and low knowledge participants; the high knowledge members would have to articulate their ideas clearly and the low knowledge participants could check their understanding against the high knowledge partner's responses and against the data produced during the simulation:
But, it was more looking at the data after and answering the questions. And the questions a lot of the time were kind of open-ended in a sense and you had the opportunity to talk and you had the opportunity to discuss and you may have had opinions that were different that you were working with and that's fine. It sparked a little bit of a discussion (P2).

Yeah, this particular simulation was useful because we were interacting, I was interacting with another two people so we shared our views and opinions and it was kind of a cooperative exercise. So, that was good about it, instead of grasping the whole idea by yourself and the computer. So I think, as a cooperative exercise, it was good to brainstorm about this concept (P4).

Ok, especially working with somebody else. We, [P3] and I, we'd bounce our ideas off each other. You could see this visual representation of what was going on instead of just trying to have it all inside of your head. So, you're looking and trying to find trends, bouncing your idea off the other person and eventually coming, trying to come up with some form of an answer to the questions (P12).

The group work was good because I wouldn't have been able to answer the questions on my own. Like, to be able to talk to other people and see their points of view was good because some of the questions, I had my idea but then someone else brought something up and it was like, oh yah, I never thought of that. So then, it helped you answer the question correctly or hopefully correctly (P8).

Importantly, the largest sub-category to emerge from participants' "Useful/Helpful" responses was related to improved conceptions. Twelve of the 19 respondents mentioned that the simulation was useful to them in understanding some conceptual aspect of evolution. Because the primary goal of this study was to explore how the use of a computer simulation of basic evolutionary processes, in combination with small-group discussions, affected Intermediate/Senior pre-service science teachers' perspectives of contemporary evolutionary concepts, several responses that capture the essence of this category will be cited.

My personal stance on it was that I kind of looked at it as a whole. I mean, you're running a simulation. All the ants have all these different traits and so, you're going to look at kind of the culmination of everything and saying okay, well, depending on their particular environment, this combination say, of genes, will give this particular ant an advantage. And so, I would - , when I was looking at it, I flipped back between different
graphs and I would say, okay, well, the red ants are doing well here and they're doing well here. Well, you know, what was their genetic make-up? What would make them do well? And that - , that's the way I approached it. I didn't look at each - , each genetic trait as being discrete. I looked at them all, kind of, together in kind of a holistic sense because it's - , we're looking at an individual, how that individual survived contrasting it to another. So .., that's how I looked at it. Evolutionary concepts can be very .., I think they're a bit of a paradox because they're simple and they're complex at the same time. The complexity lies in the number of different variables. Individuals are very complex and the simulation mirrored that because you didn't have just an ant that was blind or not blind. There were variations within that. And, I think that that helped to understand the complexity. But then, an ant survived or didn't survive. Passed on its genes or didn't pass on its genes. And, that .., the simplicity came through, as well. I mean, when you looked at the graphs, you'd have a population, then there would just .. one would die off or one particular population would just die off. So, in that sense, it mirrored the processes fairly well I felt (P11).

It's helpful in reinforcing the whole idea of passing on genes through subsequent generations. Like the computer simulation is very graphic in that respect. At the end of say 4 runs, or whatever, you could see that, holy cow, we started with even numbers of black and red ants and now there's all these black ants here. So, it sort of automatically, you ask the question, "why are all these black ants here"? And then you have to sort of decipher the graphs as opposed to, you know certain ones survived and why others didn't. So, that, sort of reinforces the whole evolution concept and heredity. It's even more interesting if you can compare it to the group that's right beside you because they generated totally different traits compared to the way you did it. Right? So, then they come out with a totally different type of ant than you did. So, it really highlights the whole importance of heredity and mutations and genes and how that, and how the whole mutations and genes is sort of, causes different organisms to fit and survive into a particular ecosystem versus one's that can't survive and die off (P7).

Ok, first of all the main thing I guess that was helpful is like, since I'm a very visual person, you know, you were able to visualize, you know like... Like sometimes you have to use your imagination because there was all these dots. So, you have to, a little, use your imagination and think about, ok, this is the ant colony, maybe like, you know, now like the ant movie [ANTZ], so, maybe it would add to more, helping me be more creative. Ok, this, these are actually animals and we're thinking about 2000 years, or like, you know, we're thinking about so many generations, and we're thinking like this whole thing is happening random, so, even those it's not like actual, actual, like natural, what's happening in nature, but at least it's somehow, this is one thing we were talking about, like
having a model. It's imitating, we're trying, as much as we can, as possible, to imitate the nature. Like it's randomness, it's you know, all these different possibilities, that sometimes you have one generation, you have all this population being wiped out because of flooding or something like that and then the next generation, like you know, how do you explain that and ah, ... So, it's not like a linear process, that we're saying, "Ok, if this is going to happen, this is going to happen", you know, this like the correlation. So, it would maybe help the students understand that things are not that simple in real life. It's more complex and there's lots of factors, even like you know, even it's not like one factor that's ah, forcing this kind of phenomena to happen (P13).

I think in terms of the concepts because you know it was laid out, it was simplistic for us to do, we were able to spend the time looking at the concepts. So, the questions were in a logical order, you know, they had direct references back to, "Look at this data here, look at this point on the graph", and we were able to really analyze it as opposed to just kind of skirt over it. There was a lot of opportunity, a lot of varied questions, some of them were talking about, natural selection, versus adaptation. Like, it exposed a wide range of evolution. I know the focus more was the natural selection element of it but we did look at, you know, adaptation and the idea of fitness came in and there was a lot of opportunities for why you think this happened. So, it wasn't a lot of, "This is what happens, this is evolution." It was, you know, here's a situation, you know, based on this principle, why do you think it occurred?". Or even sometimes, "what do you think this principle is?", and then, based on what you thought the principle was, you know, you were making up an assumption. And a lot of the times, it was not as accurate as it could have been but it was based on what we knew, prior knowledge (P2).

I thought it was really neat. I like computer simulations in general. I think it's ... it's a fun way to be able to do something that ..., if you were to do it in real time or to ..., to actually man ... use actual manipulations and things, it would be too tough. I can give you another example. Like, with math and you have the graphing calculator, you can easily run a series of, like, if you're doing probability, you can run a series of trials, like, in five minutes. Boom, boom, boom, boom. And you can generate the data and it's just as valid as if you had done it yourself sort of thing, but, a lot more efficient and because of ..., you can use computers, you can get a lot more stuff and you can cover a lot more content and you can probably even cover stuff that you may not be able to do, just in general, in a class. Like, I can give you another example as well. Like, with the chem programs downstairs where you can do actual experiments, the chem lab, where you can actually do dry runs. Sometimes, some of those experiments, you wouldn't be able to do in a classroom setting just because the materials, it's dangerous, there's a huge explosion, etc. So, with the computer, you can
still see exactly what you get and it's a fairly good representation of it without actually doing it. So, I like computer simulations (P15).

Like the "Useful/Helpful category, participants' responses pertaining to those aspects of the simulation they found "Confusing/Not Helpful" contained sub-categories. Here, four sub-categories of responses emerged: 1) Time, 2) Need for Answers, 3) Computer Graphics, and 4) Too Many Variables.

Three participants noted that they would have liked to spend more time with the simulation. Recall, however, that the time participants were asked to spend using the simulation in this investigation was intended to mirror the amount of time a teacher in a high school would spend doing a similar activity. This constraint was part of the study's design because it was reasoned that, if this group of participants, with university degrees in science and mathematics, felt some sense of pressure because of insufficient time for learning the concepts, then this likely would be the case for learners in high school as well.

Perhaps if we have the simulation twice, or spend more time on one run, and pay attention more to the individual characteristics, let's say for example, focus on one gene, and see what happens to the gene throughout its history. Then it would be, I guess, that would also contribute to the overall education (P4).

It wasn't enough time, like I would really have ... I know, you know things are busy and stuff like that, but I think we would could have put an extra half an hour there and you know instead of being a little bit rushed. (P13)"

A somewhat surprising category of responses emerged among some participants. Three individuals expressed having a need for answers to the questions that were posed during the simulation. These participants wanted "the" answers:

We saw what the graphs were but then there was no explanation afterwards to see if we were right or wrong, to see whether our hypotheses were right or wrong and I know that sometimes there isn't a right or wrong. We just wanted to generate hypotheses but I kind of would have liked follow-up information... [The simulation was] not helpful in the sense that I would have liked to know the actual, or possible answers to why some of the graphs were the way they were. So, we generated
hypotheses, but then we had no way of checking to see if that was the case or not (P1).

What else? ..., The questions are quite confusing too because maybe I'm not sure of the answers, so that's why I find it confusing sometimes (P10).

A number of participants (six) suggested that computer graphics used in the simulation were not helpful or useful to them in understanding evolutionary concepts. The general notion expressed in these responses was that realism in the objects (e.g., ants, food) and events (fighting, mating, dying) would have helped them maintain their attention and motivation while running the simulation. However, this simulation was chosen specifically because it lacked distracting graphical displays. Realism was assumed to be a distraction and contributor to anthropomorphic responses that could otherwise be devoted to learning about the underlying concepts.

The only thing that would be even neater is if the simulation software was designed so the ants actually looked like ants. So, you see little ants running around instead of little dots. Cause it's hard to keep track of ..., well, this is supposed to be an ant and this is supposed to be food and this is supposed to be poison and you know. Then there's the whole, you know, they can see, they can't see, they can fight, they can't fight, so ... (P3).

I think if you're aiming it for students in high school level, I think their attention is more for what they can see. Especially with how technology is right now and Internet and they see all these wonderful web pages and things like that. It'll help keep their interest (P9).

An improvement would be maybe, so you could actually see the ants being eaten by the anteater or something, instead of just dots, you know (P12).

The last and largest sub-category of responses related to aspects of the simulation that participants found confusing or not helpful was having to attend to too many variables. Thirteen participants responded with comments that fell into this category. Most participants expressed the idea that they were overwhelmed by the complexity of the interactions among all the variables that were used in the simulation. Particularly difficult for most was the notion that the virtual ants had a 16-bit (binary), nine “gene”
genotype (Appendix E). That is, there seemed to be some difficulty regarding the connection between an ant's genotype and its phenotype.

At the beginning when you, when there was all those strands [gene scheme] and those different colours and they - , the zero stood for this, I found that really confusing. The first thing I thought of was, if that was in a classroom setting in high school, they'd find that really confusing. I wouldn't even tell them what it was. I wouldn't know if I would tell them what it was 'cause that would just confuse them more. It was neat though to see everything kind of going on. Those strands [gene scheme] at the beginning with the different traits. But, the thing is, you've got to know that stuff 'cause you got to know that this guy can't see, this guy can see the ant-eater, this guy can only see this far away. But, yah. That was the only thing confusing. That's it (P8).

The ..., the difficulty I had with it, I think, was keeping track of all the variables because there were - , there were so many different little variables in terms of, you know, can they .. how far can they see food? Are they poison-resistant? This and that and the other thing. And so, I think that the second time we did it, it was a lot easier because I .. I'd already gone through the manual and I kind of .. I had a familiarity in terms of the different genetic traits that these ants possessed. So, I think that running through the simulation, obviously, is not as helpful as the end product. I mean, when you're looking at the graphs, it's when it all hits home. And when you do the graphical analysis and - , and look at which ants survived, which ants didn't and why. So, I think once you've gotten a hold of what all the different genetic traits and what they mean, and you've ran through the simulation and .. and then, at that point, you're actually going through the graphical analysis, then it hits home. But, I think you'd have to go through it probably more than once .. to get a hang of it (P11).

Like you can't do all the statistical data that, ok now, save this, go to the next step, and save that, and go next without having time to, maybe do one trait at a time. Just look for poison you know, resistance, once. And then, let's say, digest, because it takes, I don't know, some people like me, I'm a kind of person who likes to know every detailed thing about that concept before I move to the next one. And sometimes having more examples does not make things more easier. I like, you know, it's better to have like fewer examples, or like you know, few traits but go into more depth and you know (P13).

I guess, for a beginner, it might be a bit confusing that there are so many variables. Uah, I know you can look at each one by itself but you know how it is when your, you have your control and then you change all those things, I think for maybe a beginner in the evolution concept, they might be a bit confused with that (P9).
The final category that emerged regarding aspects of the simulation participants found confusing or not helpful was related to prior knowledge. A total of five participants expressed views that were either self-oriented or student-oriented. Self-oriented responses expressed some frustration of wanting to know more about the events transpiring in the simulation, but, because the respondents did not have the requisite knowledge, they were somewhat dissatisfied with the process of using the program (e.g., see P13 and P2 below). Student-oriented responses expressed the idea that it was important to acknowledge students' understanding of evolutionary terms because the meaning they ascribe to these terms could be radically different from how a biologist might use the same term (see P17).

I guess the thing I learned about, out of that simulation is that I really didn't learn that much about evolution out of the, myself personally, I didn't learn that much out of it. But, I did learn that you've gotta be careful about your words. What words you're using and how you're using them. I think that's what I learned most out of the evolution in the exercise. ... Yeah, the language is important because it made me realize that just when you're talking about it, that you can use the language in different ways and it can be interpreted incorrectly or correctly. And, so you've gotta be careful about what ideas you're planting. Would the ideas, - , you've gotta be careful in how you're going to measure your objectives when you're teaching about evolution because the language they're using may not actually be the ideas, .., They may be using the language in a way that doesn't actually reflect evolution. It may just reflect their misconceptions (P17).

Like first, I was just thrown into it, at the beginning. I didn't know what to expect and maybe that was the purpose of this whole experiment that you were put into. But, if I just had a little background on ... or maybe, were we given any information? No, the first time we were not given any information at all. Like, ok, this is a simulation and stuff. The second time I had a better goal of what this whole thing, what the process was about. But the first time, I was like kind of, wow, like trying to learn all those things at the same time and I wasn't expecting what's going to happen in the minute to the next. ... And maybe also like you know, having, I would suggest maybe, this simulation could also be like a very good thing when you do an intro, but it would also be a little helpful if they had a little background on, you know, before they actually do this simulation. That way they would be more interactive and, you know, they will say, wow, you know, let me... (P13).
I guess there was an assumption of some form of, kind of prior knowledge with it and that would be the only thing because it did ask questions, like what's the difference between adapting and adaptation, or whatever the question was. But, so, in cases like that, there is some sort of assumption of prior knowledge. I'm assuming that the way it's set up is that this is something that you wouldn't necessarily use, you know. You'd have to use it in the context of looking at these concepts before hand. And, for us, some us have biology backgrounds and some of us didn't, some had more evolution than others. So, obviously, I mean, you know, from listening from the tapes, there's a wide variety probably of ways of looking at, and some people might have described something, they're talking about the exact same thing but do it in a completely different way because you're looking at it from a different way. So, the only thing that I would say is just looking at it in terms of, I think there was an assumption of background knowledge. And, some people may not have had that... But, I think it's a matter of knowing that that's there and making sure you incorporate that into how you're using it. And if you're using it, then make sure that, things as simple as reading graphs, things like that. For us [pre-service science teachers], you're assuming, ok, we can read a graph, we can interpret this, but not everybody can. And, just the questions were sometimes, what is this and then relate, use this. So, other than that, that was about it (P2).

The final category that emerged were responses related to personal, and unique experiences. Three participants shared their own experiences as a result of being a part of the investigation. The first response was a candid expression regarding a personal belief about the efficacy of computer based learning (see P1). The next response (P13) raised thoughts related to deep personal and emotional issues that arose as the ideas of evolution became clearer. This participant freely shared her concerns and thoughts and felt comfortable that they would resolve themselves as long as there was an opportunity for reflection. The third participant shared ideas related to why some misconceptions were evident in responses she made throughout the study.

I didn't - , Just me personally, I don't, I like when I'm in a learning situation to be in a classroom environment where I actually see the teacher and not necessarily faced with the computer in front of me and when the computer's there, I don't know, I just didn't find that ..., we did a lot of guessing (P1).

I mean, if, this is one thing that you know, if, when you're recruiting people for this kind of project, they really have to be interested and, like you know. Like you have to have an interest, motivation, and not just, like the extrinsic, like you know the reference letter, the money, like it's not ... that's not what attracted me to this project to begin with and, you would
agree that, you know, if you have that kind of motivation, and then you say, ok, let me get rid of it and you will be ..., and it won't be that effective and that way, we will give feedback of get involved into it. I was really, you know, emotionally and physically involved with this project because it affected me in a way that, you know, like really affected me deeply. And I start asking lots of questions ... why I need to be a science teacher? Can I handle it? That was my big question and that's what involved me, it was intrinsic motivation (P13).

Well, I don't think I really understood natural selection before I did the simulation. And a lot of it has to do with the fact that there was a massive teacher's strike in [a school board] when I took OAC biology that lasted 6 and half weeks. I missed the entire evolutionary unit. It was up to each one of us to read it on our own at home if we wanted to. And I just didn't get it because I never heard anyone explain it. So, I did the best with what I had and my belief was the misconception which is that, you know, a being will adapt their genes to suit the environment. Which isn't true. It happens over years and happens over a genetic mutation which then improves that mutation. So, I mean I had the misconception, I mean I was the perfect proof of misconception existing because it was self taught. So I think that the whole demonstration and doing the exercise and stuff really helped to dispel my misconceptions because now, if I have to teach it, biology class at any level, I certainly won't perpetuate it. So, that was extremely beneficial and it was fun (P6).

Open Comments

At the conclusion of the final interview, participants were given an opportunity to discuss any aspect of the study that came to mind. To facilitate such responses, participants were asked, "Do you have any comments or questions about any aspect of the study?". Very little additional probing was used, so the comments cited below were predominantly spontaneous.

Participants' open comment responses fell into seven broad category types: 1) Benefits, 2) Queries, 3) Suggestions, 4) Knowledge, 5) High school, 6) Group work, and 7) No Comments). Similar to the responses for the simulation questions noted above, a brief description of each category will be discussed, followed by one or two responses that are illustrative of the category. Again, in some instances, several responses will be examined because of their significance to the overall goals of the study. Some responses fell into more than one category type. Thus, there were rarely any absolutely discrete categories. However, the "No Comments" was a discrete category. Two participants had
no additional comments or questions to discuss when asked. Unless otherwise noted, all quoted responses within a category were produced by different participants.

One major theme that emerged from the comments was related to the benefits a participant felt accrued from being in the study. The benefits ranged from superficial (e.g., "It was good.") to more reflective comments about the nature of what was learned. Interestingly, all of the responses (n = 13) in this category were "self" focused. That is, benefits were described in terms of what the study had accomplished for the participant, personally. In addition to what participants gained personally, 2 of the 13 indicated that what they had learned from being in the study might benefit their future students. For example, P4 indicated, "I think overall the study was very organized. Beneficial of course, from every aspect. From my own individual aspect, for my potential future students' aspect, yes."

Other common personal benefits related to uncovering misconceptions and improving general knowledge of evolutionary concepts. Several other comments related to the fact that participation in the study had provided participants with exemplary resources that would assist them with teaching and learning about evolution by natural selection:

I enjoyed it. I really did. I think that it helped to..., for me, to kind of get back into it and to think about it again. And, to realize that it .. there is not a lot of attention paid to it and that there are a lot of misconceptions and I - , it forced me kind of to think back to my misconceptions and re-examine ones that I may still have and hold today (P11).

I would say that it's increased since what I knew before we did the study but I wouldn't say that I'm totally comfortable with it (P18).

I'm really glad I did it because, and it may not reflect in my answer right now, but, it just helped me weed out a lot of misconceptions that I had had. I don't remember the last time that I looked at Darwin's theory of natural selection. Yeah, it just weeded out a lot of misconceptions (P12).

For me it was a chance to get a lot of resources, you know, be able to look at something I hadn't done a lot of. So, that's why I kind of chose to do it, cause, it's beneficial to me, cause you know, all these resources and other people and things like that (P2).
The resources are wonderful, even though I didn't get a chance to read all of it, but I think hopefully one day I will get a chance. Like, I kind of, there are lots of resources (P13).

The last common benefit that some participants mentioned was how they perceived the simulation in the context of the study as a whole. Two of these responses were related to the study per se and one was related to the simulation as a tool for learning:

I find the lesson plan helped us a lot to understand. Because just by doing the simulation I won't understand anything. But, by doing the lesson plan I can think back, oh, I did that simulation and I did that and then in the lesson plan we can incorporate what we did in the simulation into the lesson plan (P10).

And this provides that, it's like, the less of delivering process. It's more of an inquiring - , like, allow people to inquire and think more. So, that's a good aspect of it, I think (P19).

I think that's really important because you have to show them it's a real-life .. like, that's a big thing with me, is being able to relate it to stuff that you'd actually do in reality. That's why I say with the computer simulations, like, when you're teaching it, the one thing that you say is, you know, I'd love to be able to show this to you in class like this, but for time constraints or whatever, I can't do it. But I can show you on the computer and it's just as valid. It's exactly what you would do in a classroom setting only it would take us like, you know, like a few weeks to do. Whereas a computer can crunch it out in a shorter amount of time. So, I think there's a lot of validity in that (P15).

This last quote indicated that the participant was thinking in terms of how to approach teaching evolutionary concepts and how students might be able to understand them by using the simulation as a tool for learning. This kind of response was noteworthy because, although it was unique, it did emerge spontaneously and was precisely the kind of perspective the simulation was meant to engender with participants.

The next largest response category was related to queries. The majority of queries dealt with participants wanting to know how the study's data were going to be used and interpreted:

So, having listened to maybe, some of the tapes and stuff from our simulations and other things and our discussion of answers amongst
ourselves, what have you learned, if anything about some of the misconceptions, we as a group who are going to go and teach other people, what kind of misconceptions have you been made aware of? (P3).

What did you find overall, in general, like? (P14).

The other type of query responses that emerged from participants' open comments were related to how the simulation should be employed within the classroom. These questions, unlike the responses in the benefits category, were entirely student-focused:

Well, one question I have, is would you use this in the classroom situation? Like, I know you would but, like what grade levels would it be for? (P5).

If you'd be doing this with a class, would you introduce them to the simulation right off the bat or would you go through and discuss concepts and then, you know, get them to go through it and discuss it afterwards? (P11).

The author's responses to all queries were discussed with participants after the interview had ended and were not audio taped.

The next most common type of general responses provided by participants were suggestions. All five responses in this category were related to how they felt some aspects of the study could have been improved. The prominent theme for these suggestions pertained to the amount of assumed background knowledge participants had before being introduced to the simulation:

I think I would discuss concepts first. Yah. Because -, because there's so many different variables, I think that the examples that we used with, for example, the cheetah or the salamander, you're looking at one particular trait. And although that's not an accurate representation of what probably happens, that it helps them to start thinking in terms of natural selection. And I think if you're to kind of throw them in the simulation right away, there's too many variables interacting and I think it may confuse things or may perpetuate misconceptions in a sense (P11).

It could have been because of the time limit, like, is it something outside, it's a separate, a week thing, it would be a lot better. Like, a week thing, emphasize on the evolution and all that. Not only in terms of concrete knowledge, like the background, reading and .., and then you have the simulation (P19).
The importance of the amount and nature of prior knowledge assumed on the part of participants in this study will be addressed more fully in the discussion.

Responses related to knowledge of evolutionary concepts was also an important theme that emerged in this portion of the final interview. Although the number of participants providing responses in this category type was small, the nature of their responses was considered critical because it reveals that they were honest and reflective enough to admit to significant gaps in their knowledge of evolutionary theory. The admissions are important because these participants appeared to realize that evolutionary concepts cannot be treated in a superficial manner if there is any expectation for meaningful learning:

I think, something that a lot of people, you don't know, or you know little bits of it. You've heard of fitness, you've heard natural selection, but you don't know how to bring it all together. So, I think that's good and that's part of the reason I chose to do the study versus do the reflection. Because, for me, even though I've studied biology, I don't know a lot about evolution (P2).

Going back to the questions that were in the book, I know, I had a couple that were just, if you weren't there, I would have been smoked because I didn't understand what they were trying to ask. Remember, we were there for a while, going at it? There was a couple of things that kind of went over my head (P5).

I was just going to say like, before we started, before I did this, I didn't know how much I knew about evolution and I took a course and I thought I knew enough but doing all the research and planning all the lessons, I know that I didn't know enough about evolution. So, I would not be comfortable teaching it (P8).

At least I realized, oh my God, there is a lot of stuff in evolution. Like -, in school, I learned this part. I we did do this part but it's just two classes and they just feed us the formula and sort of .. and, I tend to think it to be more of a truth. Like, less question about it and .., okay, I accept it as it is. Or, probably, this is the way it is (P19).

Interestingly, comments related to the relevance of high school emerged as a theme. This is also an important finding because it pertains to one of this study's goals. Specifically, if there is any progress to be made in helping high school students to
improve their understanding of evolutionary concepts, then it must begin with those who will be providing students with their introduction to the topic: high school teachers. As these comments indicated, there are strong allusions to the critical role (positive and negative) that high school teachers have had in these participants' conceptions of, and attitude towards, evolution. Two of the four responses are cited here. Although the second one is relatively long, it is worthwhile presenting here because of its scope in dealing with the theme of the importance of high school teachers in students' understanding of evolution:

I started .. in high school, in OAC, there's an evolution component. And granted, it was left 'til the very end but we had an excellent introduction. It was in-depth and we had about a week and a half and our OAC teacher was fantastic. I mean, she dealt with misconceptions right off the bat, the first day - , and I incorporated that in my lesson plan. The idea of .. okay, you give me adaptations you foresee for the year 2000. She went through Lamarckian explanations of evolution. And so, she just banged the misconceptions on the head the first day. And from that day onwards, my whole thinking about evolution completely flipped around (P11).

I know, this is for true, in the high school that I was going through, that, there was actually two biology teachers. One of them, he wasn't religious but he said, like this evolution theory, because I went to a very multicultural school, and he said, he knows it's going to be tough for lots of people so he avoided the topic, which I was in his class and instead we just did the, you know the, Hindenberg, [Hardy-Weinberg], kind of, you know only the calculation, the equations, you know, it was like maybe 1 or 2 lessons on that and that was it and we played with marbles... He didn't go into it too deep. Yeah. We didn't go in too deep about evolution theory and he just sort of went through another topic. We did more on ecology and stuff like that and I don't know whether it was helpful or not but that was it. And the other class, the teacher was like, no, we have to take it and then he was talking about evolution theory and there were two students who left his class. They were angry at him and maybe it was because of the vocabulary and the way that he was presenting it. Really, that's ah, that kind of, there is some, that kind of students would not take any kind of challenge to what they believe, and so we have to be careful. Saying, ok, there is this alternative views at the same time because, maybe, since like I begin to understand even when I took university. There was a lot concepts I didn't understand because I didn't have a good background on this especially when it comes to the micro level life where everything is based, the whole of biology of the life of the cell is based on evolution and selection of ... natural selection. Like I kind of like understood it, but not ... you know what I mean? So, it was a little like greyish area which I
somehow passed. So, I thought I don't have to face it anymore, but guess again, you want to be a science teacher so you have to rethink this whole thing again. And it kind of helped me on how I want to present it to the students (P13)

The last theme that emerged from this portion of the final interviews was related to participants' perceptions of being placed into groups for the purposes of completing most of the study's tasks. Of the four open comments related to group work, two were positive and two were negative. However, because no probes were used, no additional details regarding this assumption were explored. The positive comments were:

I thought it was very useful. In terms of preparing lesson plans, it was a lot of fun. I liked working in my group. I know that not everyone had as wonderful an experience as I did and I think some people would find that frustrating. I think it’s important. I can see why you assigned groups. Because that's kind of random, itself, in finding out how certain people work together and those kinds of things. And if the same people work together all the time, then the idea is to get to know people in this program, so it is social. But I know that for some people, they found it a real struggle because they couldn't meet with their group member or they had different ideas (P6).

Yeah, it just weeded out a lot of misconceptions, especially working with somebody else instead of just having your own train of thought. You bounce ideas off each other, like hey, maybe it's not that way, it's this way. And you outlined a lot words that, you know, were kind of using synonymously, but shouldn't have been (P12).

The negative comments regarding working in groups dealt specifically with group members' interactions:

I think we really have to be careful, like sometimes I was a little bit emotional, when it was say, that that oh, this misconception, that misconception, and it's not misconception. Like there's certain beliefs, like, you know deep, like even when we were doing the group project, that was one of the discussions that I had was one of my group members, like don't call it a misconception. Like I was getting emotional. It's an alternative view of the way that we view the origin of life and you know God created everything for purpose and there's no such thing as accident and stuff like that right and this is what I was raised to believe from, like you know, since I, the beginning (P13).
Just what I found with people you obviously have to deal with different working styles and different expectations that people have and, especially around that time which is like, end of November, beginning of December, you have so many things due. And, I ended up kind of, you know, starting it on my own and saying, look we, you know, have to do this. I mean, and ah, it got very frustrating for me, you know (P2).

Summary

Two of the eight groups submitted lesson plans that were conceptually focused and covered most of the fundamental principles of natural selection. The other six lessons contained various conceptual errors and either ignored or treated important ideas regarding natural selection in a superficial manner. Generally, all of the lesson plans tended to under-estimate the complexities and concepts involved in natural selection. As a result, arguably, all of the lessons submitted by participants over-estimated the amount and type of content that could be covered with students at a grade 11 or 12 level.

The concept maps revealed a great deal of variability in the extent to which participants have a unified conceptual framework of the principle components of evolution by natural selection. The primary difficulty participants had in constructing their maps was linking concepts with meaningful terms and phrases that would convey the nature of the relationships. Overall, 14 of the 19 participants (74%) created concept maps that contained various types of misconceptions. The remaining five participants created concept maps that had no obvious conceptual problems. However, these five maps lacked important conceptual details and, as a result, were considered incomplete and vague.

With respect to applied knowledge of evolutionary concepts (i.e., the Cheetah question), most participants (74%) expressed some type of Darwinian conceptions for evolutionary processes. However, for the less familiar, counter-intuitive question (i.e., the Salamander question), most participants (95%) expressed predominately Lamarckian or some other non-Darwinian conceptions.

Participants' views on the resources used (information and activity-based) and their views on the efficacy of the simulation in helping them to learn evolutionary concepts was examined with the aid of a questionnaire. Distinct patterns emerged in the use of both types of resources (information vs. activity-based) with respect to the type of resource that was helpful for understanding evolutionary concepts. The readings were
reported to be useful by an equal number of high and low knowledge participants. The Internet resource was reported as useful predominantly by low knowledge participants while high knowledge participants reported that their own personal knowledge was most useful in helping them to understand evolutionary concepts. Forty-seven percent of the participants reported that running the simulation was the most useful activity-based resource followed by creating the lesson plans (37%). The process of working in groups was an activity that only 3 of 19 the participants reported as the most useful activity-based resource in helping them to understand evolutionary resources.

Four major categories emerged regarding participants' ideas about the usefulness of the simulation in helping them to learn evolutionary concepts. The first category, “Useful/Helpful” contained three sub-categories (Interface, Group Work, Improved Conceptions). The largest and most important of these sub-categories, improved conceptions, dealt with participants' beliefs about how they thought the simulation worked to improve their understanding of the basic concepts of evolution. The second category, “Confusing/Not Helpful”, contained four sub-categories (Time, Need for Answers, Computer Graphics, Too Many Variables). Of these sub-categories, participants expressed some frustration that the simulation required them to examine too many variables as they interacted with the simulation. The third category of responses acknowledged the vital role that prior knowledge plays in learning about evolutionary concepts. Finally, three participants shared some personal beliefs and experiences about the usefulness of computers as a learning tool, the emotional consequences of participating in the study and a brief historical account of why certain misconceptions about evolution were evident.

Last, when participants were given an opportunity to respond with open comments about the investigation as a whole, only 2 of the 19 participants did not provide any additional comments. For the remainder of the participants, there was a “self-oriented” perspective with respect “Benefits” accrued from being in the study. Some “other-focused” (e.g., future students) responses emerged in the “Suggestions” and “Queries” categories. Surprisingly, the influence of “High School” emerged as an important category for some subjects. A category of responses related to “Group Work” revealed a mix of positive and negative sentiments from a small number of participants.
Chapter 7
Discussion: Knowledge, Intentions, Epistemology

The principle of natural selection is so logical and so obvious that today it can hardly be questioned at all (Mayr, 1997, p. 191).

Overview

The primary goal of this study was to explore how the use of a computer simulation of basic evolutionary processes, in combination with small-group discussions, affected Intermediate/Senior pre-service science teachers' perspectives of basic evolutionary concepts. Four interrelated sub-goals and four research questions were also explored in the context of this primary goal.

The first sub-goal was to assess Intermediate/Senior pre-service science teachers' current conceptions of evolution. The results indicated that approximately two-thirds of the participants had a poor understanding of basic evolutionary concepts, with only 2 of the 19 participants demonstrating a strong comprehension. The second sub-goal was to explore the relationships among Intermediate/Senior pre-service science teachers' understanding of contemporary evolutionary concepts, their perspectives of the nature of science, and their intentions to teach evolutionary concepts in the classroom. Knowledge of evolutionary concepts was found to be a good predictor of participants' intentions to teach evolution by natural selection. However, knowledge of evolutionary concepts was not found to be associated with any particular science epistemology perspective (e.g., see Table 7, p. 56). The third sub-goal was to analyze and to interpret the small-group discussions as members interacted with the simulation. An analysis of the discussions revealed that the simulation evoked a wide array of correct conceptions as well as misconceptions. Participants' ideas about events in the simulation tended to be influenced by prior knowledge, although many of their conclusions about evolutionary concepts (some correct, some incorrect) were also guided by inferences pertaining to graphical data produced by the simulation. Overall, the most prominent effect of participants' use of the simulation was a heightened awareness of just how complex evolutionary concepts can be to understand and to teach. Thus, participants recognized the critical role of language, the inadequacy of their own prior knowledge, and the importance of gene-environment interactions in their emerging conceptions of evolution by natural selection. The fourth sub-goal was to assess the extent to which the standard
practice of creating a lesson plan on the topic of natural selection could affect Intermediate/Senior pre-service science teachers' conceptions of evolutionary theory. All of participants' lesson plans contained various types of misconceptions related to natural selection and most tended to overestimate what could be accomplished in a 70 minute period.

Several specific research questions were examined. The first question was whether this group of Ontario Intermediate/Senior pre-service science teachers had a level of understanding of evolutionary concepts similar to the levels of understanding reported in the literature for comparable samples of subjects (e.g., Brumby, 1984; Zuzovsky, 1994). The findings indicated that this study's sample of pre-service science teachers had a level of understanding that was very similar to samples of subjects in other studies. The second question explored whether Intermediate/Senior pre-service science teachers' knowledge of evolutionary concepts could aid in the prediction of their intentions to teach evolution by natural selection. Participants' knowledge of evolutionary concepts was found to be associated strongly with their intentions to teach evolution by natural selection ($r = .42$). The third research question addressed whether individuals who endorsed a “positivist” view of science would have higher scores on a test of evolutionary knowledge when compared to participants who endorsed a more “relativist” view of science. Overall, participants' perspectives on the “positivist/relativist” scale were “relativist” in nature. In fact, participants who had better knowledge of evolutionary concepts tended to have stronger relativist views when compared to those who had weaker knowledge of evolutionary concepts. The last question of interest in this study examined whether the use of a computer simulation of basic evolutionary processes, in combination with small-group discussion, would be an effective way to reveal the nature of Intermediate/Senior pre-service science teachers' conceptions of evolution. The simulation was found to be highly engaging for participants and a very effective method of encouraging participants to speculate, question, discuss and learn about important evolutionary concepts.

In chapters 7, 8 and 9 the results that addressed these goals and research questions will be interpreted and discussed. Each of the three results chapters (i.e., 4, 5, 6) will be considered in three parallel chapters respectively (i.e., 7, 8, 9). For the purposes of clarity, some of the findings within a section from a results chapter will be discussed under a single heading. For example, some of the results pertaining to the EKS that were
discussed separately in the chapter 4 will be combined into a single subsection in chapter 7. Thus, chapter 7 will address the questionnaire data (i.e., the EKS, the ITEQ, and the NOSS). Chapter 8 will discuss participants' use of the simulation in phases two and four of the investigation (see Table 6, p. 51). Chapter 9 will address the lesson plans participants created, their concept maps, their answers to applied questions, their use of the resources available in the study, their perspectives on the simulation, and their comments about the study per se. Chapter 9 will explore the educational implications of this investigation and include a discussion of the limitations of the study and offer some concluding remarks.

EKS, ITEQ, and the NOSS

Knowledge of Evolution. None of the literature reviewed for this study involved a Canadian sample of participants (e.g., Bishop & Anderson, 1990; Brumby, 1984; Demastes et al., 1995a; Jensen & Finley, 1996; Zusovsky, 1994). As noted previously, these investigations have reported that there tends to be widespread confusion, numerous misconceptions and an overall poor level of understanding of basic concepts related to evolution by natural selection among a large majority of their subjects. The results from this study, which involved an Ontario sample of pre-service Intermediate/Senior high school science teachers, were very similar to the findings of studies involving subjects from other countries. That is, approximately two-thirds of the participants in the current study were found to have a poor understanding of basic evolutionary concepts. Furthermore, of those individuals from this sample who were able to pass the Evolution Knowledge Survey (EKS) (i.e., 10 or more of the 20 questions were answered correctly), only two were found to have a good understanding of the concepts (i.e., EKS = 15/20).

Because the EKS was used throughout this investigation for several different purposes, it is important to discuss it here in some detail. First, it is possible that the low EKS scores observed for participants in this study reflect some type of bias within the EKS itself. As with any measurement instrument, an individual's score is composed of a true score (e.g., what the individual actually knows about evolutionary concepts) plus some measurement error (e.g., variation from the true score due to misinterpretation of the question or due to misunderstandings because of poor item wording) (Schwarz, 1999). Any biases in the EKS questions, items and wording would result in an instrument that was not specific enough (i.e., did not address relevant concepts) and/or
not sensitive enough (i.e., did not permit detection of differences among how various respondents expressed their understanding of the concepts) to assess participants' true understanding of basic evolutionary concepts. However, as discussed below, it appears that the EKS was both appropriately specific and adequately sensitive. Therefore, participants' EKS scores were accurate reflections of their knowledge regarding basic evolutionary concepts.

When questioning the extent to which participants' EKS scores reflected what they really know about basic evolutionary theory, a quantitative perspective would require an examination of the psychometric properties of the EKS (e.g., item reliability, test/retest reliability, construct validity). The EKS was selected for use in this study because analyses of this nature had already been conducted by the researchers who constructed the original scale (Jensen & Finley, 1996). Moreover, because the focus of this study was qualitative and descriptive, verification of the instrument's psychometric properties was not conducted. However, "triangulation", a qualitative method of determining the efficacy of a measurement instrument, was explored (Mathison, 1988; Meehl, 1981). That is, assessment of a given construct (e.g., knowledge of evolutionary concepts) may be considered more trustworthy if that construct is examined from a number of different viewpoints (Guba, 1981).

In this study, triangulation on participants' knowledge of evolutionary concepts was possible because they not only completed the EKS, but also answered questions during the simulation, created concept maps, and answered applied questions in the final interviews. In addition, responses on the EKS itself were examined by an independent expert, who agreed with the author on participants' answers for 93% of the questions. Generally, individuals who had higher scores on the EKS tended to supply more detailed and conceptually accurate answers to questions asked during the simulation and final interviews, and created more comprehensive concept maps when compared to those with lower EKS scores.

However, this trend requires some qualifications. The EKS was useful for identifying participants with conceptual difficulties, but primarily when their scores were low. That is, participants who had lower EKS scores (i.e., 10/20 or lower, n = 14, 74%) exhibited consistent difficulties across all of the other tasks (i.e., simulation, concept maps, final interviews). For those participants who had higher EKS scores (i.e., 12 or greater, n = 5), the EKS was less trustworthy in providing an accurate picture of what
participants knew about evolutionary concepts. For example, one participant's EKS score (i.e., 15/20) was judged to be a minor overestimation of his knowledge of evolutionary concepts because some of the answers provided during the simulation and final interview contained misconceptions that were not revealed by the EKS. In contrast, another participant's EKS score (i.e., 13/20) was clearly a substantial underestimation of her knowledge of evolutionary concepts because, when given the opportunity to supply protracted answers to questions (e.g., during the simulation and final interviews), the true extent of her sound conceptual understanding was revealed. Importantly, these qualifications regarding the trustworthiness of the EKS do not alter the overall finding that about two-thirds of the participants were considered to have a poor understanding of basic evolutionary concepts. Thus, because of the availability of other data that examined participants' knowledge of evolutionary concepts, it is reasonable to conclude that the EKS was a generally trustworthy assessment tool for exploring participants' understanding of these concepts.

With respect to specific questions on the EKS, no discernable pattern regarding participants' specific conceptual strengths or weaknesses was evident. Recall that Table 9 (see p. 66) listed all of the EKS items and the percentage of participants who answered each particular question correctly. The questions addressed a wide array of misconceptions (e.g., teleology, Lamarckism, the role of chance, anthropocentrism) and basic evolutionary concepts (e.g., randomness, adaptations, fitness, natural selection, mutations). Of the 10 questions that focused on evolution misconceptions (i.e., 16e, 16j, 16d, 16f, 16i), five were answered correctly by more than half the participants, and five (i.e., 16a, 16c, 16h, 16g, 16b) were answered incorrectly by more than half the participants. With respect to the questions that dealt with conceptual understanding (e.g., 1-5, 7-10, 12), the results indicated that concepts such as adaptations, fitness, and natural selection were topics that most participants did not understand well. These specific conceptual problems are very similar to those encountered by subjects in other studies (e.g., Bishop & Anderson, 1990; Demastes et al. 1995a; Demastes et al. 1995b; Jensen & Finley, 1996). Generally, the EKS revealed that participants' difficulties with evolutionary theory is not confined to a single identifiable conceptual problem. Rather, most participants tended to exhibit different types of both conceptual difficulties and misconceptions regarding basic evolutionary concepts.
There is one noteworthy aspect of three specific EKS items (e.g., 3, 9, 10) that deserves further mention. Interestingly, these conceptual questions were answered correctly by 74, 68, 63 percent of participants, respectively, and dealt explicitly or implicitly with death (e.g., "did not survive", "dog population dies", "many deaths", respectively). None of the other correct answers for the conceptual or misconception questions focused on a specific theme. Recall, that "death and dying" also emerged as a prominent focal point for some participants as they discussed events that occurred during the simulation. This discovery raises the possibility that focusing students' attention, as Mayr (1997) has suggested, on the "nonrandom elimination" (i.e., death) aspect of evolutionary events, may lead to improved conceptual understanding. This finding warrants further investigation because not only does it suggest obvious curriculum strategies, but, it also invites speculation about how and why such a focus would operate to influence conceptual change.

Another finding that requires some discussion is the relationship between the reported number of full-year undergraduate biology courses taken and participants' knowledge of evolutionary concepts. Recall that there was a weak relationship ($r = .21$) between participants' EKS scores and the number of reported full-year undergraduate biology courses taken. This association may be explained, in part, by the fact that while participants may have reported taking undergraduate biology courses, there is no way to know how, or if, the curriculum in these courses dealt specifically with the topic of evolution. In fact, as the final interviews revealed, some participants reported taking three or four full-year undergraduate biology courses, yet stated that they had not covered any material related to evolution since high school.

The fact that participants in this study performed so poorly on the EKS despite an average of four full-time undergraduate biology courses is a cause for concern. If Dobansky's (1973) biological truism, "Nothing in biology makes sense except in the light of evolution", has any merit, then a large majority of the pre-service science teachers in this study began their Faculty of Education programme with significant gaps in their understanding of the only theory that provides the foundation for every aspect of modern biology. Furthermore, it is highly probable that all of the participants in this study will secure employment with the expectation that they will teach various grade levels of biology as part of their teaching load. The findings in this study indicate that most will be under-prepared to do so in the area of evolution. Thus, it is worthwhile speculating
briefly about some of the possible causes for how such a weak relationship between participants' knowledge of evolution and the number of undergraduate biology courses taken could arise.

First, it may be that these individuals completed undergraduate courses in biology that did not contain any substantive content regarding evolution. Highly specialized courses in biochemistry, genetics or ecology could all be taught without reference to their evolutionary origins. However, even complex biochemical pathways like Krebs cycle are examples of evolutionary adaptations (Scharmann, 1993). Thus, a simple question like, "How did such a chemical system arise?" cannot be answered without reference to several evolutionary principles.

Second, a more likely explanation is that students are being exposed to evolutionary concepts but complex interactions between the curriculum, aptitude, and personal attitudes preclude adequate learning of the content. For example, Bishop and Anderson (1990) noted that teachers may erroneously assume evolutionary concepts are easier to understand than they actually are for most students. Lawson and Thompson (1988) have shown reasoning ability can account for as much as 20% of the variance in students' abilities to learn evolutionary principles. Cobern (1994) and Scharmann (1993) have noted that until students' personal views on the subject are acknowledged and legitimized, many students are likely to be, a priori, less inclined to examine the relevant information.

Last, as the instrument (i.e., the EKS) used in this study revealed, a course test that purports to assess one's understanding of a particular concept could fail to reveal significant misconceptions. Thus, a student could perform well, for example, on a multiple choice final exam while still being unable to apply the knowledge in a meaningful way. In fact, as discussed in the next section, one of the benefits of using the simulation was that when participants attempted to use their prior knowledge of evolution to explain complex problems or situations, misconceptions were frequently revealed. In short, there is unlikely to be any straightforward explanation for the lack of a stronger relationship between the number undergraduate biology courses taken by participants and their knowledge of evolutionary concepts. However, as discussed subsequently, there are some additional insights provided by the results from the Intention to Teach Evolution Questionnaire (ITEQ) that do shed some light on the nature of this relationship.
**Intentions to Teach Evolution.** The Intentions to Teach Evolution Questionnaire (ITEQ) was used in this investigation to explore some of the elements that might affect whether participants would actually teach the topic of evolution with their students. Unlike the EKS, however, there was no other means by which to evaluate the trustworthiness of the ITEQ results.

Overall, the results indicated that there were demonstrable differences in this sample of Intermediate/Senior pre-service science teachers regarding their intentions to teach evolution by natural selection. The results also indicated a fairly strong positive relationship between knowledge and intentions ($r = .42$). For 79% percent of the participants, their ITEQ category (low or high intentions) could be predicted by knowing their EKS category (low or high knowledge). Like previous research using Ajzen's (1985) theory, the attitude dimension of the ITEQ was found to be more important in determining intentions relative to either the subjective norm (SN) or the perceived behavioural control (PBC) dimensions (Crawley & Koballa, 1994; Lumpe et al., 1998; Petty & Cacioppo, 1981).

The most noteworthy aspect of the subjective norm dimension of the ITEQ was related to those items where there were no differences between the low intention-low knowledge group (LL) and the high intention-high knowledge group (HH). Specifically, unlike other research which has examined the influence of religion, it appeared to have no significant influence on participants' intentions to teach evolution by natural selection (Cobern, 1994; Lawson & Weser, 1990; Moore, 1982; National Academy of Sciences, 1998; Scott, 1996; Smith, 1994; Smith et al., 1995). This conclusion is also supported by item seven in Table 17 (see p. 82), which indicated that the LL and HH groups held identical positions with respect to the impact of religion on their intentions to teach evolution by natural selection. These results are encouraging because it suggests that participants in this study, while acknowledging the influence of their religious organizations, were unlikely to let this potential influence affect decisions about their science teaching. This finding also fits with participants' overall perspectives on the nature of science. That is, by acknowledging that the influence of their religious organization is relatively unimportant in their decisions to teach evolution by natural selection with their students, participants are being consistent with the "relativist" epistemological position they espoused on the Nature of Science Survey (NOSS). Again,
however, the small number of participants in each group requires that these conclusions be regarded as tentative until data from a larger sample can be examined.

The results from the perceived behavioural control dimension were equally encouraging. That is, the LL group was more likely than the HH group to believe that a loss of control over external factors, such as time and relying on available text books, could negatively affect their decisions to teach evolution by natural selection. It is reasonable to conclude that both of these factors are related to acquiring the necessary knowledge to teach adequately lessons on evolution. That is, the LL group was more likely than the HH group to believe that they would not have the time to do so, and that if they did, that the primary resource that teachers would be most likely to rely on (i.e., textbooks) would be an inadequate source of such knowledge (Swarts et al., 1994). These findings are encouraging because unlike internal factors related to perceived behavioural control (e.g., personal beliefs, ability), external factors can be addressed much more easily. For example, it is relatively less difficult to devote more time to learning about evolutionary concepts (for teachers and students) and to finding or designing exemplary curriculum resources than it is to try and change individuals' personal beliefs. This point relates directly to the third dimension of the ITEQ: attitudes.

The results from the attitude dimension of the ITEQ were the most noteworthy. First, unlike the subjective norm (SN) and perceived behavioural control (PBC) dimensions, there were large percentages of items that differentiated the HH and LL groups. Specifically, 71% of the items exceeded the criterion value established for distinguishing between the LL and HH groups. Also, recall that the overall range of attitude scores for the LL group (-0.3 to 5.1) was smaller compared to the HH group and that all of the scores were positive. On the other hand, the range of attitude scores for the HH (-2.3 to 7.9) group was larger and contained values that indicated a negative attitude towards some items compared to the LL group.

One way to interpret this smaller range in attitude scores at the lower end is that it represents an underestimate of the LL groups' perceptions of the potential negative consequences (e.g., upsetting and offending students, and creating controversy, see Table 17, p. 81) of teaching evolution by natural selection compared to the HH group. Furthermore, in contrast to the HH group, the smaller range in attitude scores at the upper end represents an underestimate of the potential benefits of teaching evolution by natural selection (i.e., see items 5, 19, 9, 10, 16, 1, 17 11, 13, 21, 20, 12 in Table 17, p. 82). In
general, these underestimates (i.e., of the potentially negative and of potentially positive aspects of teaching evolution by natural selection) can be seen as a generalized tendency of the LL group to avoid the topic. As discussed subsequently, this interpretation is supported by research involving similarly controversial subject matter.

Particularly noteworthy in the last list of items noted above are those that deal with evolution as it pertains to humans and those that deal with science epistemology. Each of these two topics will be discussed next. First, in comparison to the HH group, the LL group had relatively less positive attitudes about teaching evolution by natural selection when it entailed associating humans with their evolutionary past (see items 17, 13, 21, and 20 in Table 17, p. 82). The reasons for some participants' relative unwillingness to acknowledge our (*Homo sapiens*) evolutionary roots has been discussed by other authors (e.g., Dennett, 1995; Nickels, 1987; Scott, 1996) who have offered similar reasons as to why they believe this might be the case. Scott's summary of these reasons is the most succinct:

This is illustrated by the fact that there is a direct correlation between the degree of theological conservatism and the amount of scientific evidence for evolution that is accepted. The most theologically conservative accept only physics and chemistry; the less conservative accept some of biology (for example, some evolution of non-human forms), and only the most theologically liberal accept human evolution. Ironically, the scientific evidence for the evolution of our species is far better than that for most other mammalian genera. I believe human evolution is not accepted predominantly because of ideological commitments (p. 517).

The last sentence in this passage leaves unanswered why ideological commitments, or to use Cobern's (1994) term, "world view", should lead to a rejection of human evolution. It may be that having certain ideological commitments or a particular world view can lead to less than a full evaluation of all the available information that would allow one to assess critically the veracity of the evidence for or against evolution by natural selection, particularly as it pertains to humans. Unfortunately, no measures of ideological commitment or world view were used in this study. Thus, it is not possible to confirm or reject this speculation because the extent to which the LL and HH groups differed on these dimensions is not known. Nonetheless, what remains unanswered is why having a specific ideological commitment or a particular world view precludes adequate information evaluation or acquisition.
There are independent lines of evidence which speak to this question that are worth noting. The first comes from research dealing with human sexuality. Fisher, Grenier, Watters, Lamont, Cohen, and Askwith (1988) found that having strong affective responses and holding specific cognitive beliefs and attitudes towards certain kinds of sexual information can affect knowledge acquisition. Specifically, medical students who scored lower on a measure of their comfort with sexually related themes and material (e.g., masturbation, sexual orientation, human sexual anatomy) had significantly lower scores on a test of sexual knowledge when compared to those who were more comfortable with sexually oriented material. Furthermore, those students who were less comfortable with sexually related material were significantly less likely to attend a course on human sexuality and significantly less likely to benefit from the course compared to those students who were more comfortable with sexually related material. Thus, for some individuals, topics that may be, a priori, emotionally charged, evoke anxiety, or that contain information contrary to one's deeply held beliefs (i.e., ideological commitment, world view) may be examined and learned in a perfunctory manner. Is it possible that the mere thought of having to learn about evolution could evoke affective, behavioural, and cognitive responses that make effective learning of these concepts more difficult? If this speculation is even partially true, then Cobern's (1994) suggestion that students' prior thoughts and feelings regarding evolution must be considered before specific content is taught, seems to have some merit.

The other line of evidence regarding why some individuals may examine information about certain topics selectively comes from the domain of cognitive psychology. Stanovich (1999) noted that a great deal of human information processing is affected by what is termed the "fundamental computational bias" (p. 192). The bias is characterized by:

... b) the tendency to contextualize a problem with as much prior knowledge as is easily accessible, even when the problem is formal and the only solution is a content-free rule, c) the tendency to see design and pattern in situations that are either undesigned, unpatterned, or random, d) the tendency to reason enthymematically -- to make assumptions not stated in a problem and then reason from those assumptions, and e) the tendency toward a narrative mode of thought" (p. 193).
Furthermore, as Stanovich (1999) noted, this tendency to contextualize a problem with prior knowledge, (i.e., projecting one's prior beliefs onto the current information) may have an insidious side effect. Specifically,

The knowledge projection tendency, efficacious in the aggregate, may have the effect of isolating certain individuals on “islands of false beliefs” from which -- because of the knowledge projection tendency -- they are unable to escape. In short, there may be a type of knowledge isolation effect when projection is used in particularly ill-suited circumstances. Thus, knowledge projection, which in the aggregate might lead to more rapid induction of new true beliefs, may be a trap in cases where people, in effect, keep reaching into a bag of beliefs that are largely false, using the beliefs to structure their evaluation of evidence, and hence more quickly adding incorrect beliefs to the bag for further projection. Knowledge projection from an island of false beliefs might explain the phenomenon of otherwise intelligent people who get caught in a domain-specific web of falsity and because of projection tendencies cannot escape (e.g., otherwise competent physical scientists who believe in creationism). Indeed, such individuals often use their considerable computational power to rationalize their beliefs and to ward off the arguments of skeptics (p. 248).

As discussed in the next section, this explanation warrants further examination because not only was the influence of prior knowledge an important one but each of the other elements of the fundamental computational bias (FCB) (i.e., c, d, e) appeared to operate from time to time as participants used the simulation. Moreover, implicitly and explicitly, all of the items listed as components of the FCB suggest that sound prior knowledge may be a key factor in mitigating the bias. This explanation raises some interesting possibilities regarding when, where, and how in the chain of events, compensatory curriculum strategies may be most effective. It also invites the question of whether some of the participants in this study were creating their own unique evolutionary islands of false beliefs. Figure 12 is a summary of how a given epistemological stance, in the context of such factors as “mere thought”, “fundamental computational bias” (FCB), and “knowledge projection” (KP), could operate to affect one's intention to teach evolution by natural selection.

Interestingly, the conditions and outcomes that operated to produce the model in Figure 12 are very similar in structure and content to a model proposed by Fennema and Franke (1992) regarding the importance of beliefs and prior knowledge in teaching mathematics. This model is presented in Figure 13 for the purposes of comparison.
Figure 12.
A summary of the possible factors influencing one's intentions to teach evolution by natural selection.

Pre-Conditions

Epistemological Stance: Ideological Commitments or World View
(A type of prior knowledge)

Mere thought of topic can lead to affective, behavioural, and cognitive responses that can make learning the topic more difficult.

Prior knowledge is not adequate, given the nature and complexity of the concepts

Awareness of the degree of commitment to a given epistemological stance, the extent of their FCB, or the extent of their tendency for KP will vary from individual to individual

Outcomes

Topic becomes emotionally charged or controversial

Information may be learned selectively or perfunctorily

Fundamental Computational Bias & Knowledge Projection

Intentions to teach a given topic vary

Size of Islands of False Beliefs vary
The second aspect of Table 17 (see p. 81) that is significant is that the other two items which showed large differences between the LL and HH groups deal specifically with the two most fundamental aspects of science epistemology: 1) the nature of scientific evidence, and 2) the means by which such evidence is evaluated: critical thinking. Importantly, these two items are directly related to the first issue just discussed (i.e., beliefs about human evolution and prior knowledge). In other words, it may be that the LL group has less favourable attitudes towards these items compared to the HH group precisely because it would necessitate a more complete and less superficial examination of evidence that could undermine and/or challenge one's ideological commitments or world view. At least one implication of this is that one's epistemological stance may need to be oriented towards a perspective that acknowledges the kinds of evidence that societies which are technologically oriented and knowledge-based typically produce. Why? Stanovich (1999) explains:

Because postindustrial societies increasingly create more and more decontextualized information processing environments (insurance forms, HMO rules, graduations requirements, taxation statutes), the cognitive
environments of present society -- and the environment of the future -- puts a premium on the ability to selectively override the fundamental computational bias, an ability that studies have shown to be related to both algorithmic-level computational capacity and the thinking dispositions of intentional-level psychology (Stanovich, 1999, p. 193).

Again, however, these speculations cannot be examined in the context of the data produced from this investigation. However, as discussed next, participants' perspectives on the nature of science gathered in this study do offer some interesting insights into this issue.

**Perspectives on the Nature of Science.** Participants' perspectives on the nature of science, as assessed by the NOSS (Appendix B), can best be summarized as non-traditional, multidimensional and moderate. Importantly, one category, "scientific approach to investigations" showed the strongest consensus among this sample of Intermediate/Senior pre-service science teachers regarding their views on the nature of science. The question that explored whether participants who exhibited a "positivist" perspective would have better knowledge of evolutionary concepts compared to those who endorsed a more "relativist" position revealed that those individuals who were "relativist" tended to have better knowledge of evolution. Additionally, there were only minor differences in participants' perspectives on the nature of science as a function of their knowledge of evolutionary concepts.

There is wide agreement among contemporary philosophers of science that because the practice of science is a human endeavour, it is by definition, inherently value laden and is influenced by social, political, and economical factors (Herschbach, 1996; Hodson, 1988; Pera, 1994; Rudner, 1953). It is encouraging that this sample of participants appeared to share this emerging philosophical view of scientific practice. For example, results from part A of the NOSS indicated that about two-thirds or more of the participants felt that errors are an inherent part of the scientific process and that the "scientific method" does not guarantee results. This is not the view typically held by those with a more traditional perspective of scientific practice. Results from part B of the NOSS (Nott & Wellington, 1993) revealed a similar picture. Recall that negative scores on any of the five Nott and Wellington dimensions were indicative of a more traditional view of science. Only one dimension (Inductivist/Deductivist) produced a small negative mean value; the other four dimensions had small positive mean values. These results, coupled with those from part A of the NOSS, suggest that, overall, this sample of
participants holds more contemporary, less traditional perspectives on the nature of science.

How did these participants come to adopt this contemporary philosophical view regarding the nature of science? First, it is unlikely that the non-traditional views held by participants was due to the philosophical position espoused by the professor who taught these students in their Bachelor of Education program. The NOSS was administered during the third week of classes, before the professor had begun any formal introduction to the philosophy of science. Thus, while a contemporary philosophical view on the nature of science may have been reinforced as the participants progressed through their programme, it was not a factor when they completed the NOSS. Second, although gender was not considered to be a factor in this investigation, it does deserve consideration as a possible reason for the presence of a non-traditional view of science for the simple reason that 14 of the 19 participants in the study were female. It would be an interesting follow-up investigation to examine if any of the results regarding the presence of a more contemporary philosophical view on the nature of science espoused by participants in this study was related to gender. Last, it could be that courses within the Bachelor of Science programs that these participants attended while completing their undergraduate degrees have begun to espouse a less traditional philosophical view on the nature of science. Again, it would be interesting to examine this possibility by interviewing participants and asking them to provide more details about their views on the nature of science and to discuss some of the influences that have led them to adopt such a perspective.

As noted above, participants who exhibited a "relativist" perspective tended to have better knowledge of evolutionary concepts compared to those who endorsed a more "positivist" view. The rationale for exploring this relationship between participants' evolution knowledge and epistemology was predicated on the definitions for the respective philosophical views provided by Nott and Wellington (1993). According to them, a positivist view of science posits that "The laws and theories generated by experiments are our descriptions of patterns we see in a real, external objective world. To the positivist, science is the primary source of truth. Positivism recognizes empirical facts and observable phenomena as the raw material of science" (p. 111). Conversely, relativists believe that "the 'truth' of a theory will depend on the norms and rationality of the social group considering it as well as the experimental techniques used to test it."
Judgements of truth of scientific theories will vary from individual to individual and from one culture to another, i.e., truth is relative not absolute" (p. 111).

Recall that none of the philosophical views espoused by any participant in the study could be considered distinctly positivist or distinctly relativist. In fact, only three of the 19 scores on the positivist/relativist (PR) sub-scale were negative (i.e., positivist) and none of these scores was high enough to approach even the moderate level in the positivist range. Nonetheless, it is possible that holding a more relativist view about the nature of science allows one to appreciate the complexities of some evolutionary concepts. For example, understanding that there are complex dynamics involved in gene-environment interactions (e.g., that fitness is relative to the environment) appears to be similar to the relativist's notion that what one adopts as the truth is relative to the constraints of a particular social context.

However, as Nott and Wellington (1993) have noted, their scale was to be used only as a means of initiating discussions regarding the various perspectives on the nature of science. It was not meant to categorize definitively individuals into one particular epistemological stance or another. A more thorough exploration of the relationship between the positivist/relativist philosophies and knowledge of evolutionary concepts would require: 1) a more sensitive and specific PR scale, 2) a much larger sample size that included individuals with both a broad range of knowledge in evolution and diverse perspectives on science epistemology, and 3) interviews with participants to probe for their views on the nature science. In fact, a broader exploration of the relationship between science epistemology and knowledge of evolutionary concepts in general is warranted because, as discussed next, it is unclear that participants' science epistemology acts in any way to influence their knowledge of evolutionary concepts. This finding is somewhat unsettling because it suggests that the processes and products of science tend to be seen as largely independent when, in fact, they are inextricably interrelated.

As the results indicated, there were very few differences between the low and high knowledge groups with respect to their views on science epistemology. Moreover, to the extent that the VOSTS captures a broad array of science epistemological perspectives, participants' views on the nature of science were, overall, quite varied. Interestingly, a similar kind of discontinuity between epistemological stance and outcomes was also found by Hodson (1993) and Scharmann and Harris (1992). Hodson found that in his sample of teachers, there was very little connection between their views on the nature of
science and how they taught various science topics. Scharmann and Harris (1992) found no relationship between improved knowledge of evolution and the philosophical position regarding the nature of science for the subjects in their study.

This discordance between one's philosophical views on the nature of science and the outcomes and practice of science may not be all that surprising if one's epistemological stance is seen not as a "perspective", but rather, as an "attitude". In this light, the more general the attitudinal question that purports to reflect a given position, the less likely there will be any identifiable association between the attitude itself and specific outcomes (Petty & Cacioppo, 1981; Worchel & Cooper, 1983). For example, it is often the case that individuals will endorse global attitudes that are environmentally friendly (e.g., "polluting is harmful to the environment") without exhibiting concomitant behaviours that would be associated with such a position (e.g., walking or riding a bike instead of driving). Many of the items on the NOSS (Part A and B) can be viewed as examples of general science epistemological attitudes (e.g., Question 1 - "Scientific observations made by competent scientists will usually be different if the scientists believe different theories"). As such, there is unlikely to be any substantial association between respondents' answers to general questions like these and specific behavioural outcomes (e.g., defining natural selection). It would be relatively easy to test this notion by designing a nature of science survey that was based on more specific epistemological questions (e.g., "A competent scientist, (A), made the observation that water became solid at 0 degrees centigrade. Would another competent scientist, (B), make a different observation if she believed a different theory than scientist 'A' for why water freezes.

The interest in understanding the relationship between an individual's philosophical stance towards science epistemology and their knowledge of evolutionary concepts is not a trivial one. The sheer volume of independent scientific evidence that supports the theory of evolution by natural selection is probably unparalleled in science. Yet, as noted earlier, when it comes to accepting the evidence, a paradox appears in many people's reasoning. Specifically, when it comes to accepting evidence for the major foundational theories in chemistry and physics, where there tends to be far less direct empirical support for such theories (e.g., no one has yet observed an atom, an electron, or a quark), there is almost blind, dogmatic acceptance among teachers and students at the primary and secondary school levels. Only among chemists and physicists at the tertiary
level are there revolving debates regarding new theories and the evidence that purports to support them.

In stark contrast, because the evidence is so compelling, there tends to be dogmatic, unquestioning acceptance of the tenets of evolution by natural selection among biologists at the tertiary level; evolution is a fact for the vast majority of biologists. Yet, among teachers and students of biology at the primary and secondary school level, there tends to be hesitation and often outright rejection of the evidence that overwhelmingly supports the theory of evolution by natural selection. For example, new species can be created in the laboratory (Ayala, 1982; Ridley, 1996). One can touch, see and create genes. Variation abounds; of the six billion plus people on the planet no two are identical. Multimillion year old fossils can be gathered on a Sunday afternoon walk, and a trip to the agricultural building during a local fall fair allows one to observe with one's own eyes evidence of how selective breeding can dramatically alter the morphology, physiology, psychology, and behaviour of non-human animals.

To be clear, the paradox is this: primary and secondary students and teachers tend to accept, without question, less than compelling evidence for phenomena in the domains of chemistry and physics. However, these same students and teachers will knowingly ignore, disregard and reject far more extensive and cogent evidence when it addresses the only known theory in biology that parsimoniously accounts for the functionality, diversity and unity of life on the planet. Unquestionably, understanding the nature of this quintessential science epistemology paradox is critical if progress is to be made in helping students and teachers understand evolution (National Academy of Sciences, 1998; Scott, 1996; Smith et al., 1995).
Chapter 8
Discussion: Using the Simulation

*The surprise consists precisely in the emergence of familiar macrostructures from the bottom up -- from simple local rules that outwardly appear quite remote from the social, or collective, phenomena they generate. In short, it is not the emergent macroscopic object per se that is surprising, but the generative sufficiency of the simple local rules (Epstein & Axtell, 1996, p. 51-52).*

Overview

The computer simulation used in this investigation modelled basic evolutionary processes by using simple, computer-generated organisms ("ants") which behaved and interacted according to simple, "bottom-up" rules (Casti, 1997), and that existed in an uncomplicated, changeable, virtual environment. Simulations of this type, which model natural phenomena like evolution, have been described as "conceptual simulations", "relational models", and "process simulations" (De Jong & Van Joolingen, 1998; Snir et al., 1995; Windschitl, 1998). Participants were placed into small groups (dyads or triads) for the purposes of exploring, discussing, and answering questions related to the events that transpired during the course of their interactions.

Overall, participants found the simulation easy to use and engaging. An examination of the discussions showed that the simulation was capable of eliciting spontaneous hypothesis generation, helped to promote lively debates and an exchange of ideas among group members, and was very useful in revealing participants' ideas (both correct and incorrect) regarding several basic evolutionary concepts (e.g., randomness, "needs" of the organism, adaptations and adapting, natural selection, fitness). Additionally, analyses of the dialogues revealed several emergent themes related to participants' thoughts regarding gene-environment interactions, death and dying, and their tendency to be anthropomorphic. However, it was difficult to assess the extent to which the simulation was able to effect conceptual change. A close examination of the discussions revealed that the degree and type of participants' concept exploration and change depended heavily on the concept per se and on participants' prior knowledge of the domain-specific content.
The Simulation

Phase 2 - Simulation for Familiarization. The most important finding from phase two was that, despite the relatively simple nature of the on-screen objects (coloured dots) and events (motion of the dots), the simulation frequently elicited participants' spontaneous conjectures about why objects behaved the way they did or why events occurred as they did. Furthermore, participants' questions were often followed by speculative explanations. This is an important finding for at least two reasons. First, it revealed that the participants themselves were active in trying to make sense of the activity in the simulation. In other words, in contrast to traditional teaching methods, where it is the teacher who structures and controls the information provided to students, the simulation offered an environment where participants were in control of deciding what information is to be considered relevant and how such information could be used to provide a parsimonious account of the simulation events.

Second, participants were spontaneously theorizing about the simulation's objects and events by using their existing ideas about evolution. Moreover, this ad hoc speculative process appeared partly as a result of simply presenting participants with coloured objects that moved across the computer screen. This kind of active interaction with the simulation relates to a growing body of literature which has shown that the efficacy of computer-based learning is due, in part, to its capacity for simultaneously engaging learners' senses of sight, hearing, and touch (Bagui, 1998; Stemler, 1997; Yaverbaum, Kulkarni & Wood, 1997). In other words, it's hard not to talk and think about objects and events that seem as if they are real. Traditional activities used to explore concepts in evolution are fairly restrictive in how and which sensory modalities are involved. Nonetheless, the evolution literature is replete with many non-computer based activities that are purported to engage learners on topics related to evolution (e.g., Dickson, 1998; Knapp & Tompson, 1994; McComas, 1994; National Academy of Sciences, 1998). However, the extent to which such activities led learners to theorize, spontaneously or otherwise, about the "organisms", their actions, and their interrelationships with each other and the environment is not discussed as a potential benefit of these activities. In fact, it is reasonable to argue that such theorizing will not materialize because many of these non-computer-based activities, by their very nature, cannot dynamically establish that there is any interrelationship among organisms'
phenotypic and genotypic characteristics and their environment (e.g., see McComas, 1994; or Activity 3, National Academy of Sciences, 1998).

The importance of learners actively theorizing about why some ants had certain characteristics or behaved the way they did in the context of the virtual environment cannot be overstated. Evolution is a process of change that occurs over protracted periods of time and that involves the intimate interaction of an organism's phenotypic characteristics (and its associated genotype) with a given environment. The simulation appeared to make this dynamic aspect of evolutionary processes both implicitly and explicitly salient to participants; cause was linked with effect (e.g., more food in the environment leads to increasing population sizes), and actions and events were tied to observable outcomes (e.g., ants that could avoid poison tended to survive, those that could not tended to die). Evidence for the implicit connection between the ants and their environment can be found in participants' frequent referrals to environmental characteristics that could affect the ants' survival (e.g., amount of food, appearance of the ant eater, fighting with other ants). The connection was made explicit by information contained in the manual (e.g., the gene scheme) and the fact that participants were required to establish and change the environmental parameters before and during the execution of the simulation.

What remains only partially answered from the data collected in this investigation is the extent to which participants' observations and concomitant hypothesizing were related to current theoretical accounts of evolutionary events. As Snir et al. (1995) and others (e.g., Cromer, 1997; Posner et al., 1982; Strike & Posner, 1992) have argued, making these associations is a critical component of the conceptual change process. However, it appeared for most participants that these connections were weak, at best. For example, recall that in phase two participants were asked to discuss their ideas about the target of selection (i.e., was it genes, individuals, populations, or species?). This question was asked because it is a concept that must be understood by anyone hoping to understand evolutionary events (Ridley, 1996). Furthermore, as Dawkins (1982) noted, many errors in thinking about how and why evolutionary events occur can be avoided if a gene-level view of selection is adopted.

However, biology teachers must be able to link descriptive accounts of what transpires as organisms and their genes interact in an environment using the guiding explanatory theories which can account for such interactions (Jimenez-Aleixandre, 1994).
It is not possible to provide a coherent account of the diversity, unity and function of life on the planet without understanding how natural selection operates at the gene level. By analogy, this would be like trying to explain chemical reactions to students by describing the reactants in terms of their superficial properties (e.g., colour, taste, smell, cost).

Coherent, predictive, and parsimonious explanations of chemical reactions are predicated on reference to the fundamental properties (e.g., bond angles/strength, molecular weights, electron configurations) of the atoms and molecules that comprise the reaction.

In all dialogues, participants' uncertainty about how to link observations with theory was manifested by their primarily descriptive accounts of gene selection (e.g., simply discussing the gene graphs) which lacked supportive explanatory reasons (e.g., as traits that improved fitness) for the answers posited. Perhaps if participants had been allowed to interact with the simulation for a longer period of time, or had been able to have another session in the computer lab, more discussions of these deeper issues would have emerged. Lack of time was mentioned by several participants during the final interviews as a factor they felt hampered their efforts to use the simulation more effectively. Recall, however, that the time set aside for using the simulation was a designed constraint. That is, the time allotted for its use in this study would be about the same amount of time a teacher would have to cover similar material with a grade 11 or 12 high school class. This raises the issue, which lies outside of the scope of this thesis, regarding how the topic of evolution is treated in Ontario high schools.

Another way that participants' observations and hypothesizing could be better linked to underlying theory is with the use of “simultaneous support materials” (De Jong & Van Joolingen, 1998). This approach would allow learners access to theoretically relevant information at appropriate times throughout the execution of the simulation. In fact, this process actually occurred with one of the groups in this study. For example, the members of group C were discussing their ideas about how to distinguish between the terms “adaptation” and “adapting” (phase 4, question four). The group members took advantage of the fact that the computers in the lab were able to access the Internet. They found the Web site that had been developed for this study, proceeded to read the related material about adaptations, and then began to integrate this new found information into their discussion. This event provides some anecdotal support for De Jong and Van Joolingen's (1998) suggestions and provides a fruitful avenue for further research.
In summary, phase two of the study accomplished what it was designed to do: familiarize participants with the simulation. Participants were found to be actively engaged with the objects and events in the program to the point where there was a tendency on the part of some individuals to be anthropomorphic about "dumb" ants or "stupid" anteaters. Importantly, participants began hypothesizing about why certain events occurred the way they did. However, none of the groups extended their dialogues to include deeper theoretical rationales or explanations for their speculations. More time using the simulation and appropriate support materials could have assisted groups with the process of linking their observations to important tenets of evolutionary theory.

Phase 4 - Simulation for Exploration: Overview. Participants' second interaction with the simulation was designed for the purpose of examining their understanding of important basic evolutionary concepts. These concepts included randomness, "needs" of the organism, adaptations and adapting, natural selection, and fitness.

Overall, the exchanges and themes that emerged from participants' dialogues as they used the simulation revealed a mixture of outcomes ranging from reinforcement and entrenchment of existing misconceptions to apparent conceptual change for classically difficult evolutionary concepts. In this section, analyses of the simulation data will be discussed within four interpretive themes: 1) the effects of prior knowledge, 2) misconceptions and conceptual change, 3) group work, and 4) simulations as tools for learning.

Prior Knowledge. One of the implicit assumptions of this investigation was, that because of participants' strong backgrounds in science (i.e., most graduated with Bachelors of Science degrees and all are very likely to be teaching general science) and in biology (e.g., the mean number of reported full-year undergraduate biology courses was 4.1), their overall knowledge of how theories are used in science would be good, and their prior knowledge of evolutionary concepts would be sound. As the results from the EKS revealed, the second aspect of this assumption turned out to be largely unsupported. Thus, participants' relatively weak level of prior knowledge was, in effect, a limiting factor in what information they were able to glean from using the simulation and how they were able to use it.

In a comprehensive review of the efficacy of computer simulations, De Jong and Van Joolingen (1998) had this to say about the effect of prior knowledge and using this type of computer program:
A frequently uttered claim about learning with simulations is that learners should know something beforehand if discovery learning is to be fruitful. Insufficient prior knowledge might be the reason that learners do not know which hypothesis to state, cannot make a good interpretation of data, and engage in unsystematic experimentation (p. 187).

There are strong parallels with these three outcomes of insufficient prior knowledge (i.e., do not know which hypothesis to state, cannot make a good interpretation of data, and engage in unsystematic experimentation), and three of the four elements of the fundamental computational bias (FCB) noted earlier (i.e., respectively, the tendency to frame a problem with easily accessible prior knowledge, to imbue data with patterns that do not in fact exist, and to make assumptions not stated in a problem and then reason from those assumptions) (Stanovich, 1999). These parallels make it reasonable to conclude that having access to domain-specific content knowledge can be critical in subsequent learning activities where the application and transfer of such knowledge is required. Simulations are examples of learning activities where this conclusion applies.

Unfortunately, much of the easily accessible information that formed the basis of many participants' explanatory frameworks for evolutionary phenomena turned out to be intuitive (e.g., Lamarckian) or to contain misconceptions. The most prevalent effect of this appeared to be the generation of relatively unproductive hypotheses. Some evidence for this could be found in the behaviours of many participants as they tried to answer the questions in phase four. The dialogues revealed that participants would often jump from one gene graph to another in the hopes of finding data that would somehow fit with what they thought they knew about the concept under consideration. This attempt to find data to fit a particular hypothesis is known as the "confirmation bias" and is well documented in both the science learning literature and the cognitive science literature (e.g., Gunstone, 1991; Platt, 1964; Tweney et al., 1980).

There was a notable exception to this pattern. In one conversation, one participant (EKS = 15, the highest observed score) was looking for evidence to support the possibility that something equivalent to evolution by natural selection had occurred in the simulation (phase four, question five). His attempts to provide an answer to this question appeared to be based on his sound prior knowledge of natural selection. He openly hypothesized that if natural selection were occurring, then it would make sense to
look for changes in the pattern of gene frequencies after any changes in the environment had occurred. Note that the sole reason participants were asked to change the environmental parameters at the midpoint of the simulation, was to make salient the impact of how environmental changes can affect gene frequencies. This participant then directed his attention to such a point on the gene graphs (e.g., see Figure 3 at T4 or T5, p. 62) and proceeded to make a tentative conclusion that he thought supported his claim.

The previous example illustrates how sound prior knowledge can guide subsequent reasoning in a situation that calls for the application of concepts. Unfortunately, without such background information, the focus of many participants' discussions never approached the level where they could make the connection among their observations, their proposed hypotheses, and any important tenets of evolutionary theory. As many science education researchers have stressed, without this observation-theory link, promoting conceptual change can be difficult (e.g., Cromer, 1997; De Jong & Van Joolingen, 1998; Posner et al., 1982; Snir et al., 1995; Strike & Posner, 1992; Windschitl, 1998). Note, however, in this study the precise nature and form of participants' hypotheses cannot be determined from most of the exchanges that took place because unlike the example noted above, participants' hypotheses were tacit. Thus, a more complete examination of the specific hypotheses that participants generated, and the ways in which they were used to link observations to theory, would be a useful adjunct to this investigation (De Jong & Van Joolingen, 1998).

With regard to interpreting data per se, there were times when participants would dismiss and/or ignore information in the gene graphs that was seen as anomalous with their idiosyncratic ideas. They would explain these "odd" data by stating that they were "wrong", "can't be right" or "weird". De Jong & Van Joolingen (1998) cited numerous studies that revealed the tendency to interpret incongruous data in this manner is a pervasive phenomenon among learners. As commented earlier, this implicit tendency to project one's prior knowledge onto the current information can have the effect of leaving one standing on a metaphorical island of false beliefs. This outcome is very similar to an effect noted by De Jong and Van Joolingen (1998), who cited studies that showed learners to have a strong tendency to maintain only one position when espousing an explanation for a particular phenomenon. Why? Their lack of prior knowledge can lead "subjects to stick with their current hypothesis (despite conflicting evidence) simply because they have no alternative" (De Jong & Van Joolingen, 1998, p. 183).
In summary, it appears that some degree of sound prior knowledge regarding domain-specific concepts is a critical precursor to the effective use of simulations as a tool for learning. The precise nature, type and extent of this prior knowledge that learners will need in order to maximize their learning outcomes will depend largely on the phenomena that the simulation is modelling and on the complexities of the theoretical tenets underlying the model. Many participants in this investigation were unable to utilize fully the simulation as a tool for exploring some basic evolutionary concepts because of their limited background knowledge. However, as discussed next, this tendency of participants to use their prior knowledge to reinterpret the simulation data to fit their own conceptions was not universally problematic. There were times when, despite misconceptions in one area, data-driven interpretations arose in others. In these instances, participants were able to use the simulation data to make correct inferences and conclude with nascent conceptual ideas that were sound.

**Misconceptions and Conceptual Change.** The EKS was designed to reveal some specific misconceptions about evolution. It was completed individually by each participant and, unlike the simulation, there were no "objects" or "events" to focus on. Furthermore, the structure and content of the EKS questions limited the scope of how complete a picture could be drawn of participants' thoughts on evolution. In contrast, one of this study's unintended findings is that the use of a simple simulated ecosystem can be a very powerful tool for exposing a broad range of users' misconceptions about evolutionary concepts. That is, when participants used the simulation as the focal point for their ideas, in the context of discussing these ideas in small groups, the full extent and depth of some of their difficulties with evolution were revealed. One of the clearest examples of this occurred during group B's dialogue regarding the term "adapt" (see phase four, question four, p. 123). In this triad, despite two group members' assiduous efforts (including the use of examples from the simulation and the field of physiology) to help the third member of the group distinguish between the terms adaptation and adapting, they were unable to make any apparent change in her understanding. This dialogue was an example of just how impervious to change Lamarckian conceptions can be.

Why did misconceptions surface so readily as participants interacted with the simulation? The most likely factors are the dynamics inherent in small group discussions (e.g., the need for collegiality) and the relatively unassuming, but sufficient, multimedia
components of the simulation. For example, even the simulation's relatively low level of graphic realism seemed to encourage participants' natural tendencies to be anthropomorphic. This inclination was evident in some participants' descriptions of "ants" as "dumb" or "aggressive". Unfortunately, however, the tendency to be anthropomorphic has been shown to lead to conceptual errors (Blumberg & Wasserman, 1995). For example, the ability of ants to avoid poison or to avoid the anteater had nothing to do with individual acumen. Rather, it was a consequence of whether an ant possessed a particular genotypic characteristic that was manifested as a particular phenotypic response in the given environment. That participants interpreted such characteristics in human terms was utterly irrelevant to how and why the ant populations evolved. Thus, participants' anthropomorphic tendencies tended to add a layer of conceptual abstraction that hindered any deeper understanding of the basic processes.

This situation creates an obvious catch-22. The more realistic the simulation, the more likely such multimedia effects could lead to the difficulties associated with anthropomorphic ideas. On the other hand, if the simulation does not contain at least some of the fundamental dynamics between the relevant objects and events of the modelled system, learners are unlikely to realize the importance of such interactions and, as noted earlier, will lose site of the critical theoretical links that need to be made. One solution to this dilemma is to include all of the multimedia effects in the simulation, but, make learners aware of this common form of thinking before using it. In other words, it is better to make users aware of their tendency to be anthropomorphic, help them to understand why such thinking can create problems, and to give them examples of how to express biological events in less anthropocentric and more neutral language, than it is to forego the implicit and explicit dynamics of the system being modelled (Snir et al. 1995).

Overall, the dynamics of the groups and the realism inherent in the simulation, coupled with most participants' weak prior knowledge and the possible cognitive effects like the fundamental computational bias (FCB), created conditions where all participants revealed various types and degrees of difficulties with basic evolutionary concepts. It is important to point out, however, that there is ample evidence to show that it can be an extremely challenging task to provide accurate, well reasoned answers to evolutionary questions using the terms and language that do not conflate ideas or muddle cause and effect (e.g., Bishop & Anderson, 1990; Brumby, 1984; Jensen & Finley, 1996; Lawson & Thompson, 1988; Zuzovsky, 1994). For example, Dawkins (1982; 1991) frequently
prefaces his work with caveats about how he will be using certain expressions. He often asks his readers not to be overly critical if he lapses into prose that appears to convey an obvious misconception. Nonetheless, understanding, and then accurately conveying the nuances of evolutionary concepts and events is a necessity, especially for teachers.

Misconceptions notwithstanding, did participants' use of the simulation, in the context of small-group discussion, help them to understand and to convey basic evolutionary concepts more accurately? It is important to note that the design of this investigation was observational and qualitative in nature, rather than experimental. Thus, a more definitive answer to this question would require a very different research approach. However, of the six questions in phase four that explored basic evolutionary concepts like randomness, "needs" of the organism, adaptations, natural selection and fitness, the clearest evidence to support the case for conceptual change came from analysis of the dialogues regarding participants' ideas about "fitness". That is, relative to the other concepts, fitness was addressed well, but not flawlessly, by all of the groups. The following three points examine in more detail the evidence and the factors that influenced this claim. This finding was encouraging because the one question that dealt with fitness on the EKS (i.e., question 12, Appendix A) was answered correctly by only 6 out of 19 participants (see Table 10, p. 70).

First, all but two of the members of the groups were able to explain fitness in gene-centered terms for part 'A' of the fitness question in phase four (i.e., see Table 9, p. 66). It appeared that participants' conceptually accurate answers were guided by the conspicuous presence of the "gene-graphs" which helped them maintain this focus. Furthermore, the dialogues revealed that using these graphs helped participants realize that fitness was unlikely to be related to the effects of a single gene. Instead, they observed that the information contained in a single gene graph could not completely explain why some ants survived and others did not. Often, expressions like "there's got to be something else going on here" conveyed the implicit idea that both gene-gene and gene-environment interactions were operating to affect fitness. As mentioned, this was primarily implicit for most groups. Only the members of group D was able to articulate explicitly the idea that interactions were the critical factor (see phase four, question six, p. 138). However, as soon as participants' discussions became less focused on data-driven interpretations of the gene-graphs, their exchanges became more narrative in nature (Stanovich, 1999). The focus of the discussions tended to shift away from data pertaining
to the gene and move towards more abstract entities like individual ants. As a consequence, misconceptions began to appear in the conversations. Generally, the presence of gene graphs lends support to De Jong and Van Joolingen's (1998) recommendation that instructional support material of this type can help learners understand the simulated system by structuring relevant information.

Second, the ways in which questions about the simulation are framed can have significant influences on the kinds of responses learners will provide (Clough & Driver 1986; Snir et al., 1995). Part B of the “fitness” question revealed how important this idea can be. This question was designed specifically to confront participants with the common, but incorrect, idea that fitness is only related to characteristics such as being “strong”, “brave”, and “fast”. This notion was stated so bluntly (i.e., “could an ant be 'weak', 'cowardly', and 'lazy' and still be fit?”), that it was difficult for participants to dismiss the possibility outright. As discussed next, this led participants to explore numerous gene graphs in search of an answer.

Third, recall that five out of the eight groups were found to have dialogues that were categorized as having a “fitness is bravado” misconception for part 'A' of the fitness question. Also, 13 out of the 19 participants answered the fitness question on the EKS incorrectly (see Appendix A, questions 12). Yet, analyses of the discussions for part 'B' of this question revealed that seven out of the eight groups arrived at a conception of fitness that would be considered accurate. At least part of the reason for this shift appears related to the way participants used the gene graphs in the context of the question. That is, participants' answers to this question appeared to be entirely data-driven. Thus, by allowing their answers to be guided by an interpretation of the data contained in the gene graphs, participants were able to find evidence that showed their ideas of “fitness is bravado” to be largely false.

This last finding and the way in which it emerged, lends some support to one model of conceptual change. Specifically, this model states that the advancement of students' knowledge in a particular domain requires that: 1) an existing idea must be found to be unsatisfactory, 2) the new idea must be intelligible, coherent, and internally consistent, 3) the new idea must be plausible, and 4) the new idea must be preferable to the old viewpoint on the grounds of perceived parsimony and/or usefulness (Posner et al. 1982; Strike & Posner, 1992). Analyses of the dialogues suggested that aspects of the first three items in this list were true for participants because they were able to articulate a
correct conception of fitness simply by examining the evidence in the gene graphs. It is not possible, however, to confirm the extent to which they found their emerging concept of fitness "preferable" to the "old viewpoint". For example, "fitness as bravado" is not necessarily wrong. Rather, it is subsumed by a broader perspective that defines fitness as the useful and functional actions that genes have in the world as they operate through the bodies they inhabit (Dawkins, 1982). An interesting follow-up study would be to determine the extent to which participants' accurate conceptions of fitness remain stable over time.

As Duschl and Gitomer (1991) noted, Posner et al.'s (1982) model of conceptual change is unlikely to be applicable to all learners and in all domains for at least one reason that is related primarily to the fourth item in the list above. Posner et al.'s model does not address the nature of what students already know as they begin trying to learn a new concept (Duschl & Gitomer, 1991). Specifically, before a new idea can become preferable to the old viewpoint, it may not be enough to rely solely on the perceived parsimony and/or usefulness of the new idea. The reason is because it will be equally difficult for students to understand by whose standards, by what criteria, and by what process they are expected to judge such things as "parsimony" or "usefulness"?

Obviously, these are important issues related to science epistemology and have been discussed in detail earlier in this chapter. Furthermore, one must also address the reasons why learners prefer their own particular ideas in the first place. Thus, as Duschl and Gitomer (1991) proposed, promoting conceptual change requires: 1) possessing accurate information about domain specific knowledge (i.e., what to know), 2) examining a scientist's "way of knowing" (i.e., how it is known), and 3) understanding the learner's current conceptions and misconceptions. The value of this model of conceptual change as it pertains to this investigation, lies in emphasizing what learners already know and in examining their strengths and weaknesses with respect to that knowledge. As already noted, the simulation was invaluable in exploring this component of Duschl and Gitomer's (1991) conceptual change model.

Last, it appeared that the concept of fitness per se was a factor in the degree to which participants' understanding began to change. Fitness, unlike the other concepts examined in phase four, had "real" effects. That is, throughout their interaction with the simulation, participants were able to relate the presence or absence of a particular gene (or gene combinations) with a very poignant outcome; the life or death of ants.
Moreover, this connection was readily observable because participants could examine any ant's genotype, read about the specific phenotypic effect of that particular genotype, and then observe, in real time and in a "real" environment, the consequences. Thus, as noted earlier, one of the most beneficial aspects of using the simulation was that it allowed participants to reflect on the events that transpired during its execution and connect objects and events implicitly and explicitly with cause and effect. For example, participants often noted how a particular environmental factor would operate to produce specific consequences and outcomes for the virtual organisms. Importantly, all of these actions happened in the computer over evolutionary time (1000's of years). But for participants, these events happened within the space of a 70 minute session in the computer lab. Generally, these results regarding participants' success in understanding fitness (which implicitly deals with death), their success in answering the concept questions on the EKS that dealt with death, and dialogues that revealed that death and dying were an important focus for discussions, provides some evidence in favour of examining this theme as an area of concentration for curriculum design.

**Group Work.** The participants in this study were assigned to small groups on the basis of a rather large body of evidence that has shown peer discussions can facilitate learning (e.g., Brown, 1997). Additionally, recall that an attempt was made to structure the small groups so that the members of each dyad and triad had different levels of knowledge about evolutionary concepts. The groups were structured in this manner because research has shown that dyads who are moderate in disparity in stage levels of moral reasoning were reported to have a greater significant upward change in moral reasoning for the less advanced partner when compared to dyads with no disparity in moral reasoning or to dyads with high disparity in moral reasoning (Berkowitz & Gibbs, 1985; Berkowitz, Oser, & Althof, 1987).

Overall, analyses of the discussions revealed that there was a genuine attempt by all groups to provide coherent, reasoned answers that were usually supported with reference to data from the simulation. Often, lively exchanges took place regarding what evidence would support an answer and about where to look for such evidence. When disagreements arose, the ensuing debates sometimes required 15 minutes or more to resolve. As analyses of the dialogues revealed, there were also times when it appeared some members of a group merely acquiesced in response to a partner's utterances. This particular pattern of exchange made it very difficult to know precisely how the "yeah-
responder" was dealing with other's utterances. For example, it was impossible to tell from the dialogues if a participant's agreement with another was a collegial way to move the discussion forward, if the "yeah-responder" was really acknowledging a good answer and had nothing to add, if the agreement was merely an unconscious conversational filler, or, if the tendency to agree was meant as a form of social support within the dynamics of the group. In general, a closer examination of evidence that would address the specific nature of the group dynamics and its effect on conceptual change would be very useful, but is not within the scope of this thesis.

It is reasonable to conclude that interacting with the simulation on an individual basis could not have produced some of the beneficial outcomes that were seen in this investigation. For example, some of the events that occurred on the screen as the simulation was executed happened quickly. Two (or three) pairs of eyes proved useful for calling attention to unique objects (e.g., the anteater), or events (e.g., unique ant activity), and for providing clarification and alternative interpretations of the gene graphs. Also, because there was minimal input from the author, participants regularly queried each other about some aspect of the simulation that was unclear (e.g., "what are the white dots?"), confirmed and checked with each other that procedures were being carried out correctly, and most importantly, used one another as "sounding boards" as they articulated their thoughts about the question(s) under discussion.

This last point is a critical one, especially because the participants in this study are about to become teachers. There is no place for a teacher to hide in the science classroom. Teachers must be able to explain clearly and cogently what they do know and be honest about what they do not know. It was evident from the dialogues, however, that most participants had some difficulty expressing their ideas about evolutionary concepts. As noted earlier, for most, this difficulty stemmed from a lack of sound prior knowledge of basic evolutionary concepts. However, when such knowledge was present, some participants' answers were exemplary. The contextual effects of using the simulation and questioning from one's peers were important factors in evoking both types of responses. Thus, the discussions provided the opportunity for participants to check their own conceptual understanding against that of their peers and, where possible, allowed for questioning and challenging of those ideas. In short, using small groups as the unit of interaction was arguably the best way to explore participants' understanding of evolutionary concepts and to facilitate learning with a computer-based program of this
type. However, as discussed next, there were some drawbacks to using the simulation with small groups.

As Table 20 (see p. 153) indicated, it was clear that for five of the seven groups, the relatively least knowledgeable participants talked at greater length than group member(s) with greater knowledge of evolutionary concepts. Ironically, for all three triads and for two of the dyads (groups E and G), while the relatively lower knowledge participant tended to exhibit confidence and certainty that their expressed ideas were correct, their answers were often not nearly as sound as those provided by the relatively higher knowledge partner(s) in their group. Why such a pattern emerged is difficult to understand and any coherent explanation would require examining personal, language and cultural backgrounds as well as a different research approach other than the one used in this study. However, what is somewhat disconcerting about this effect is that there were times when the answers provided by the low knowledge person would go unchallenged and would be adopted by the other group members as correct when they were not. In other words, there were times when group members would reinforce a misconception simply because one individual was able to dominate the conversation.

This was an unexpected finding and points to the need for some means of monitoring participants' progress through the process of concept attainment. There are an infinite number of conceptual cul-de-sacs that could be explored and some of the dialogues revealed that participants examined a number of these as they attempted to answer the questions. Of course, exploration of this type is very important, but allowing learners to stray perpetually into a conceptual space that is supported only by intuitive ideas (e.g., Lamarckian), and then leaving them there, merely reinforces certain misconceptions. Ideally, the solution would be to help participants to regulate their own learning and to raise their awareness of those times when they should be more cognizant of the “slippery slopes” that abound, especially in science (De Jong & Van Joolingen, 1998; Dennett, 1995). As discussed next, there were some methodological interventions implemented in this investigation that were more or less successful in helping learners with this monitoring process.

Simulations as Tools for Learning. Scharmann (1993) has outlined four characteristics that are fundamental for helping students learn evolutionary concepts. These four factors were suggested as important methodological and pedagogical extensions of conceptual change models like those proposed by Strike and Posner (1992)
and Duschl and Gitomer (1991). The four elements of Scharmann's pedagogical approach for promoting conceptual change when teaching evolutionary concepts were: 1) engagement/exploration (i.e., allow learners the opportunity to express their ideas), 2) small-group peer discussion, 3) explanation/debrief of small-group peer discussion), and 4) elaborate/extend learning with related experiences and assignments.

Encouragingly, as noted earlier, the first item in this list was inherent in how the simulation was able to evoke responses in participants. The second item was an integral part of this investigation's design. However, it should be noted that “small-groups” means no more than three individuals. The results of this study suggest that group size should be kept to two individuals as it would allow both members of the group to sit comfortably in front of the computer monitor and for each person to be in control of some aspects of the simulation. Furthermore, with the use of dyads, it is less likely that one member of the group could “hide” from the conversational exchanges. Items three and four would have required separate investigations of their own in order to understand them more fully. Thus, the full efficacy of Scharmann's (1993) four tiered model cannot be determined from this investigation.

With respect to item three, as noted earlier, simulations can be augmented so that learning support materials would give users the opportunity to provide their own explanatory debriefing as they used the program. Although there were no support materials provided with the simulation in this study, it is clearly an avenue that deserves more research attention. Moreover, it follows that the less teachers find they are required to act as the purveyors of explanatory debriefings, then the more learners are likely to have been in control of monitoring their own learning. De Jong and Van Joolingen (1998) cited a large number of studies that have explored various ways of helping learners monitor their own learning as they used simulations. Two of these factors will be discussed here briefly because they are directly relevant to this study.

The first factor that De Jong and Van Joolingen (1998) suggested might be helpful in assisting users to monitor their own learning with simulations is called “model progression” (p. 189). Model progression is predicated on the idea that presenting learners with the full complexity of a simulation all at once may be too overwhelming. Instead, learners are first exposed to the system being modelled by the simulation with only one or two input variables in operation. Once users understand how these variables operate in the system, they are given access to a progressively larger set of variables
with which to explore the system. In retrospect, some elements of model progression may have been an effective means of helping participants in this study. One of the most common themes that emerged from analyses of participants' dialogues in the final interviews was that many felt overwhelmed by the number of variables (e.g., the genotypes and phenotypes). Fortunately, the nice thing about using computers as a learning tool is that making modifications to the program to improve the learning experience for users is a relatively easy process.

The second factor that De Jong and Van Joolingen (1998) suggested could be helpful in assisting individuals monitor their own learning with simulations is called "planning support". Planning support mechanisms are cognitive aids that provide some structure to the learning process by taking away certain decisions over what aspects of the simulation to explore. This approach is predicated on teachers having a detailed understanding of the preconceptions and misconceptions learners may have about the specific content domain (Shulman, 1986). As De Jong and Van Joolingen (1998) noted, this may be especially useful for learners with low prior knowledge. One important planning support mechanism is to provide questions. Obviously, many of this study's findings revolved around the answers that participants provided to questions about basic evolutionary concepts. Arguably, without the guidance and structure that such questions provided, it is doubtful, given most participants' limited prior knowledge, that a fruitful exploration of the system could have been achieved.

The last item in Scharmann's (1993) list, elaborate/extend learning with related experiences and assignments, is one aspect of his proposed pedagogical approach to conceptual change that is also inherent in using simulations as a learning tool. Specifically, the defining strength of using a simulation is its ability to repeat experiments that could otherwise not be done realistically in a laboratory setting, a large number of times. Furthermore, depending on the complexity of a simulation, the potential number of parameter sets that learners could use to explore how the system functions is enormous. Unfortunately, it seems that participants in this investigation failed to make this connection. In other words, there were no hints from any of the discussions that participants recognized that many of their ideas, queries and speculations could be tested simply by altering simulation parameters and then letting it run to observe the outcomes.

For example, participants were able to determine from the gene graphs that the presence of poison in the environment was acting as a selection pressure. Unfortunately,
none of the participants speculated about setting up a poison-free environment and observing the possible effects that such a scenario would have on the relative frequency of poison avoidance genes in the ant populations. Time constraints, participants' lack of exposure to using simulations, and the overall structure of the study were likely factors in why this aspect of using the simulation as a tool for exploring evolutionary processes did not emerge. This finding also hints at a connection with participants' perspectives on the nature of science. That is, to what degree do participants see hypothesis formulation and testing as an integral part of how knowledge advancement occurs in science? If more participants had endorsed item '8e' on part 'A' of the NOSS (only 26% of participants did, see Table 12, p. 74), would they have been more likely to view the simulation as a tool for testing and exploring hypotheses? Again, the relevance and importance of science epistemology becomes apparent in how computer learning tools, like simulations, are viewed and used by learners.

One final noteworthy aspect of participants' uses of the simulation deserves mention. As indicated in the results, two unintended, but important evolutionary concepts arose; "convergent evolution" and the "rare enemy effect". Although participants did not explore these concepts specifically, findings like these suggest that not every aspect of participants' learning experiences with simulations can be anticipated. This is an important point because it highlights the value of having a knowledgeable teacher who is familiar with how the computer is simulating the system being modelled (Casti, 1997). Thus, when such teachable moments do arise, they can be recognized and utilized to help learners see how such concepts apply to deeper theoretical aspects of the system.
Chapter 9
Discussion: Exploring Participants' Understanding of Evolution

*It is true that there are quite a number of ways of making a living -- flying, swimming, swinging through trees, and so on. But, however many ways there may be of being alive, it is certain that there are vastly more ways of being dead, or rather not alive. (Dawkins, 1989, p. 9).*

Lesson Plans

Teachers are often asked to teach subject material that is outside their undergraduate area of specialization. A very common approach that many teachers use to learn such unfamiliar material is to create a lesson plan. Typically, teachers seek out domain-related material, read about it, attempt to learn the necessary concepts, devise a teaching strategy, and then assemble and organize it all into a coherent lesson plan. In this study, participants were given approximately nine weeks to complete their lessons, were provided with exemplary curriculum materials, and were asked to create a lesson plan on natural selection with the same people they were grouped with for the simulation. The content was to be appropriate for a grade 11-12 high school class and it was expected that the material in the lesson could be covered in a 70 minute period.

Analyses revealed that the process of lesson planning, in and of itself, is unlikely to lead to any substantial gain in understanding of natural selection. There are several possible reasons for this conclusion. First, 7 of the 8 groups used various definitions of natural selection around which the rest of the lesson was planned. These definitions that participants relied on were sometimes incomplete, misleading, or wrong. Some “textbook” definitions can be notoriously incomplete and even with good supplementary material to support such definitions, a sound understanding of concepts may not come easily (Bishop & Anderson, 1990; Swarts et al., 1994).

Second, definitions, because of their superficial and succinct nature, often belie vastly more complex processes. Many participants' definitions within their lesson plans included terms like “genetic variation”, “survival of the fittest”, “degrees of adaptedness”, and many others, and failed to provided any further explanations for such terms. As the EKS and analyses of the dialogues revealed, however, most participants had various types and degrees of misconceptions about such terms. Thus, if participants' understanding of natural selection was predicated, at least in part, on their unsound
knowledge of antecedent concepts, then a conceptually accurate understanding of natural selection per se, cannot be expected to follow.

Third, although many participants were provided with exemplary curriculum materials, there is no way to know how, or if, these materials were used. This, too, however, was part of the study's design. That is, providing participants with good resources was meant to explore the possibility that simply having exemplary curriculum materials available is not sufficient for improving a teacher's own understanding of the concepts being taught. The results indicated, that participants' reported use and perceived effectiveness of the provided curriculum materials was associated with their EKS scores. This finding will be discussed in more detail in the next section. Again, however, definitive conclusions regarding what and how much participants were able to glean from the resources cannot be made using the data and research design of the current investigation.

Last, and perhaps most importantly, there need not be any necessary connection between the processes involved in creating a lesson on a specific topic and actually understanding the concepts pertaining to the material contained therein. One can always rely on sound, tried and true pedagogical approaches to make what appears to be an effective lesson (e.g., group work, videos, prepackage activities). The hope with this approach is that students are no more confused after the lesson than before they began it. If this speculation is correct, then pre-service science teachers' programs must not only address pedagogical approaches to science instruction, but they must also assume that students' conceptual strengths and weaknesses regarding certain topics will vary widely. Moreover, if weakness are found, remedial work must be a priority.

Overall, it is unlikely that many of the participants in this study will have further formal exposure to courses specifically dedicated to learning about and teaching evolution by natural selection. If this is the case, then the standard practice of preparing and teaching a lesson on this topic is probably going to lead to perpetuating the difficulties held by many of the participants in this study. Definitions of natural selection are a reasonable place to start when designing a lesson on this topic. However, a failure to understand many of the important nuances of the process, being unable to capitalize on highly effective metaphors and analogies, and not appreciating the overall importance of using the theory of evolution by natural selection as a foundational guide for all teaching in biology, will be a disservice to each new generation of high school biology students.
Thus, as noted many times in this investigation, it points to the critical role that sound prior knowledge of basic concepts can have in effective science teaching. As discussed next, there were various types of evidence that could be used to support the claim that a perfunctory knowledge base of the basic concepts leads participants to under-develop important evolutionary concepts, not just in lesson planning, but in other areas as well.

**Concept Maps**

Analyses of participants' concepts maps provided an opportunity to examine how well they were able to connect the major components of the theory of evolution by natural selection. The results revealed that only 3 of the 19 participants' maps contained no additional concepts, as asked for in this task. Fourteen out of the 19 concept maps created by participants included some type of misconception. The remaining five maps did not contain enough information to allow any conclusions about the nature of participants' understanding of evolutionary theory.

One salient feature of participants' concept maps that emerged from the analyses was that no two concept maps were similar. That is, all participants produced maps that were unique in how the concepts were interrelated, how they were arranged spatially, and in the variety of new concepts that were generated. There are a number of possible reasons for why such a wide variety of content emerged in participants' concept maps.

Recall that participants were given the following instructions about what to include in their concept maps:

After reading the instructions below, please create a concept map that details your understanding of evolution by natural selection. Note that there is no single "best" way to complete a concept map. What is important is how you view the nature of the relationships among concepts.

**Remember:**

1) You must use all five "seed" concepts in your concept map. Feel free to arrange the seed concepts in any way you would like.

2) You should try to create your concept map in such a way so that it includes **at least four new concepts** (see example below).

3) You should **relate** the arrangement of your concepts with "linking" words and phrases. These linking words and phrases should convey the essential nature of the relationship among concepts. Thus, your linking words or phrases can be nouns, verbs, adjectives, adverbs, conditional clause (e.g., if ... then ...), or any combination of these as long as you
clearly establish how the concepts are related. Please be as specific as possible when linking concepts. (Original emphasis, see Appendix H).

First, it is reasonable to assume that if there was some common understanding among participants regarding what concepts are important in the theory of evolution by natural selection, then at least some of those concepts (other than the five seed concepts) should have appeared somewhere on a large number of maps. In total, 43 different concepts were used by participants. Only nine concepts were found to be common among all of the concept maps. “Evolution” was the shared term that appeared most frequently in participants' maps and it was found in only five of them. “Fitness”, “time”, “adaptation”, and “individual” are examples of the other terms that were common among participants' maps. These four terms were shared among only 4 of the 19 maps created. Thus, when participants had to generate and to integrate other evolutionary concepts into their concept maps, there was very little agreement regarding which terms were considered important.

Second, item number three in the instructions noted above emphasized that an important part of the task was to establish the “essential nature of the relationship among concepts”. Participants produced an average of 12.2 links per concept map. However, an average of 4.8 links (40%) contained no words or phrases whatever to convey how the link related the two concepts. This finding is similar to the results that Trowbridge and Wandersee (1994) observed. These researchers reported that the difficulties their subjects had with producing meaningful, coherent concept maps of evolutionary concepts was related to insufficient or questionable detail in how concepts were linked 36% of the time.

Third, Trowbridge and Wandersee (1994) cited other factors that affected the quality of their subjects' concept maps. These same factors appeared to have influenced the quality of participants' concept maps in this study. For example, participants in this investigation were given 20 minutes to finish their concept maps. Trowbridge and Wandersee found that it took their subjects an average of approximately 30 minutes to produce a map with sufficient detail to link coherently all of the concepts. Thus, it could be that participants in this study were not provided with enough time to complete their maps, and therefore, were unable to express adequately the nature of the links between concepts. However, all but two participants had turned in their completed maps at the end of the time available.
Participants' lack of prior experience or practice with creating concept maps may also have played a significant role in the kinds of maps produced in this study. Trowbridge and Wandersee (1994) devoted two, three-hour sessions to concept mapping. In these sessions, their subjects were given detailed instructions on what was expected in a concept map and were provided with opportunities to practice and receive feedback on their maps. In this study, participants had spent approximately one hour on concept mapping and had limited opportunities to practice and receive feedback prior to completing the concept mapping task. Moreover, participants were not given explicit instructions about what was expected of them other than what appeared in the instructions (Appendix H). These conditions might explain the wide variety of new concepts generated and the unique spatial arrangements observed in participants' maps. Thus, lack of sufficient time to complete the concept maps, insufficient opportunities to learn about and practice concept mapping, and task instructions that could have been more explicit were all factors that could have led to some of the variability observed in participants' concept maps in this investigation. However, despite these factors, the variable quality of participants' concept maps and the sheer number of different concepts that they used suggested a possible curriculum strategy. This intervention will be discussed in further detail in the educational implications section of this chapter.

**Applied Knowledge**

The “Cheetah” and “Salamander” questions were asked during the final interview in order to examine participants' understanding of evolutionary concepts. The results revealed that 79% of the participants provided an answer that was considered Darwinian for the “Cheetah” question. However, for the “counterintuitive” “Salamander” question, only 1 out of the 19 participants (5%) was able to provide an answer that was classified as Darwinian.

The rather large disparity in the percentage of participants who were able to provide a Darwinian answer for one question and not the other revealed two noteworthy points. First, both questions (i.e., Cheetah and Salamander) provided some insight into how participants were thinking about an organism's traits. Importantly, the questions revealed that few participants adopted a level of thinking that could help to guide their thoughts about the evolution of adaptive traits. This conclusion is justified because had participants adopted a gene-level perspective for the traits as well as for the processes
inherent in both questions, it is likely that more Darwinian responses would have been forthcoming for both questions.

Recall that the Cheetah question asked participants to “explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 40 km/hr”. A gene-centred view of the process of natural selection was provided by most participants for this question. That is, participants responded by saying something like the following: “Some cheetahs could run faster than other cheetahs. The faster cheetahs were able to survive and reproduce better relative to those cheetahs who were slower. The faster cheetahs passed on their genes to their offspring. This would happen over and over, so that after several generations the average running speed in the population of Cheetahs would be higher than it originally was.” There are two difficulties with this type of answer that precludes effective transfer of Darwinian principles to more applied problems like the Salamander question. First, while it is true that all of the faster Cheetahs' genes would be passed on to their offspring, the question, as it was asked, deals specifically with the genes associated with running speed. In other words, participants' answers tended to be abstracted from a level above a gene-centered view of the trait per se, to the level of the organism as a vehicle for gene propagation (Dawkins, 1976). In effect, this is no different than viewing the organism as the target of selection, not the gene.

Second, had participants been able to adopt a more gene-centered view for the trait, they might have realized that the phenotypic response (increased running speed) need not have an associated “increase” in a corresponding aspect of the underlying genotype that brought about such a change. For example, a gene-level view of the trait “running speed” might lead one to speculate about selection for genes that result in a relative decrease of the number of slow twitch muscle fibres or selection against genes that cause an increase in joint flexibility. The point is, a view of selection at the gene level would allow participants to view the Salamander question from a radically different perspective. Thus, had a gene-centered perspective been adopted, the idea that “blind cave salamanders evolved from sighted ancestors” might not have seemed as implausible as it apparently did for most participants. This view of selection would also provide participants with some appreciation for the incredible complexity, multi-determinant, and interactive nature of adaptive change.

The second noteworthy point to make about the rather large disparity in the percentage of participants who were able to provide a Darwinian answer for one question
and not the other relates to the context in which certain questions are asked. Recall that participants provided written answers to both the Cheetah and the Salamander question on the EKS. Moreover, a similar question was posed to participants during the simulation (e.g., the fitness question). Thus, participants were given the opportunity to answer this question in written format, in oral format during the final interviews, and in group discussions during the simulation. The least informative answers appeared on the EKS. The answers provided there were so short that they were very difficult to score and to interpret. Analyses of participants' responses from the final interviews compared to those from the simulation showed that the quality of answers provided during the simulation was much better. That is, in the context of small group discussion, the use of the simulation's gene graphs helped to guide and to focus participants' thinking on the appropriate level of analysis, the gene. In the final interviews, in the absence of an explicit reminder, most participants' answers drifted away from the appropriate focus.

**Resource Use**

In order to understand how the various resources that participants had available to them in this study were used, the Resource Use Survey (RUS, see Appendix D) was completed. The RUS asked participants to use a checklist to rate those resources they had actually used and which they found most useful in helping them to understand evolutionary concepts. Six types of resources were available to participants during the various phases of the investigation. The six resources were divided into two broad categories, information resources and activity-based resources.

With regards to the information resources, participants who were categorized as having low knowledge of evolutionary concepts showed some preference for using the Web-based resource compared to participants who were categorized as having high knowledge of evolutionary concepts. Conversely, those who were categorized as having high knowledge of evolutionary concepts preferred their own personal knowledge as a guide for learning about evolutionary concepts compared to participants who were categorized as having low knowledge of evolutionary concepts. The readings were preferred equally by both the low and high knowledge participants.

If these resources are examined from the perspective of "amount of effort to acquire and use the resource", then the data suggest the following. Participants who were confident that their knowledge regarding evolutionary concepts was reasonably sound,
tended to rely on their current knowledge as the most useful source of information. For the most part, this confidence was justified. Thus, it is reasonable that these participants would use this "low effort, easily available" source of information. But, there was also a subset of high knowledge participants who preferred the readings over either the web-based resource or personal knowledge as the most helpful resource. Arguably, the readings can require much more effort to use as a learning tool than either the Web-based resource or personal knowledge. Yet, some high knowledge participants chose the readings as their preferred information resource. It fact, it appeared that the high knowledge group actively avoided using the Web-based resource altogether. Unfortunately, the checklist data do not allow for any conclusions about the reasons why a particular resource was preferred over any other. A possible explanation for this pattern of results is that the Web-based resource is a relatively new and unexplored source of information for most participants. Thus, it could be that when the high knowledge participants sought out additional information, they tended to stick with what had worked for them in the past; a more traditional resource like reading material. It would be a very useful follow-up study to find out exactly why these high knowledge participants preferred not to use an easily accessible resource like the Internet as a source of information.

It is important to point out that as future science teachers, despite their acceptable understanding of evolutionary concepts, the high knowledge individuals will have to become accustomed to the practice of not relying solely on their existing understanding of a particular domain of knowledge. Whatever these participants' current conceptual understanding of evolution, it is highly likely that there will be a need for regular revisions to this background knowledge as new information is added to the field. In other words, in order for these participants to maintain their current sound understanding of evolutionary concepts, they will have to continue to update their domain-specific expertise throughout their careers. In short, the tentative nature of scientific knowledge will demand a lifetime of learning.

Participants who were categorized as having low knowledge of evolutionary concepts seemed to be aware of this gap in their understanding and, as a result, tended not to rely on their own comprehension of the subject as a useful resource. Instead, this group chose the Web-based resource about two to one over the readings. Arguably, using the readings to help one understand evolutionary concepts requires more effort, can be
relatively time consuming, and is far less novel than using the Internet. Again, it is not possible to know precisely why the low knowledge group preferred the Web-resource over the readings. However, this trend invites the following speculation. Participants who had a less knowledgeable background in evolutionary concepts tended to seek the easiest accessible and available resource to supplement their understanding. If this trend is common to teachers in general, then the resources teachers tend to use most often (textbooks and possibly the Internet) should contain the most accurate and comprehensive information possible. This tendency to use an easily accessible resource may have also been the impetus behind the National Academy of Sciences' (1998) decision to make their latest textbook on evolution available at no charge on their web site.

With regard to activity-based resources, the simulation was preferred by 47% of the participants as the resource found most useful for learning about evolutionary concepts, followed by creating the lesson plan. Working in groups was the least preferred activity of the three. There were no noteworthy distinctions between participants in the low and high knowledge groups regarding their preferences for using any of the three activity-based resources. It was encouraging to find that almost half of the participants liked using the simulation independent of their current understanding of evolutionary concepts. This suggests that the simulation is a tool that can be used for assisting students with wide differences in their levels of knowledge of evolution. As noted above, it would be very interesting to examine why participants preferred the simulation over any of the other resources. This information could be very helpful in refining the types of simulation activities given to students and teachers so that all users with various degrees of knowledge of evolution could benefit from their interactions with the program.

**Perspectives on the Simulation**

During the final interviews, participants were given the opportunity to discuss their views on the simulation. Analyses of participants' responses to three semi-structured questions revealed four major themes: 1) Useful/Helpful, 2) Confusing/Not Helpful, 3) Prior Knowledge, and 4) Personal. Participants' thoughts about what they found useful about the simulation included ideas related to the simplicity of the interface, working in groups, and improved conceptions. Participants' views about what they found
confusing or not helpful about the simulation included responses related to time constraints, need for answers, computer graphics, and too many variables. The “prior knowledge” category was related to the participants' beliefs regarding the importance of users having some type of background knowledge or introduction to the simulation before using it. The fourth category, “Personal”, contained three responses that were significant because they captured unique, individual ideas or stories that were related to the efficacy of computers as a tool for learning, religious convictions and evolution, and the importance of high school in learning about evolution.

Interestingly, participants' perspectives on the simulation help to support an important claim of this study and to confirm findings from other research regarding factors that affect the efficacy of using simulations. First, an implicit assumption of this investigation was that the simulation would be a useful cognitive tool in helping users to learn about and to improve their understanding of basic evolutionary concepts. Approximately two-thirds of the participants indicated that the simulation helped them to improve their conceptual understanding of some aspect of evolutionary theory. Second, those features of the simulation that participants found confusing (e.g., not enough time, having to deal with too many variables, the importance of prior knowledge) are consistent with a large body of research that has examined the effective use and design of simulations as a learning tool (De Jong & Van Joolingen, 1998; Snir et al., 1995; Thomas & Hooper, 1991; Windschitl, 1998). Both of these results are positive because they suggest that simulations can indeed be a useful computer-based approach for learning complex science concepts like evolution. Furthermore, researchers investigating the effectiveness of simulations in educational settings appear to have identified some of the more important aspects of how best to utilize this type of computer program.

Open Comments

Participants were given an opportunity at the conclusion of the final interview to discuss any aspect of the study that came to mind. Analyses revealed participants' open comment responses to fall into seven broad categories: 1) Benefits, 2) Queries, 3) Suggestions, 4) Knowledge, 5) High school, 6) Group work, and 7) No comments.

The fact that 13 participants had “self” focused thoughts related to the benefits accrued from their participation in the study is consistent with literature dealing with teachers' concerns about pedagogy (Hall, 1985). Hall has found that beginning teachers'
concerns about their practice tend to be oriented towards personal things like having a lesson ready, having access to appropriate materials and curriculum resources, and having students like them. Teachers with more experience tend to have more student-centered concerns such as questioning whether students are learning, wondering how they can maximize each student's potential, and reflecting on the fairness of the evaluation criteria. Participants' comments in this investigation reflected a more "self-oriented" perspective. That is, one of the primary benefits participants stated they received from being in the study was related to the resources they obtained. Only 2 out of the 19 individuals who took part in this study indicated that their participation in the study would benefit their future students. Again, this low number of "student-oriented" type of response supports research regarding teachers' concerns at this early stage in their careers (Hall, 1985).

Another finding that emerged from the analyses of the open comments was that some participants (n = 5) had suggestions for ways to improve the study. As teachers, their own practice will benefit from being able to reflect on the kinds of things that did or did not go well in the classroom. The five participants who provided these suggestions offered some insightful and helpful ideas for ways that would facilitate learning with the simulation. Moreover, they were engaging in a process that is critically important to improving their own teaching.

Finally, it was a significant finding that participants spontaneously raised the issue of the importance of prior knowledge and the source of that prior knowledge in their final open comments. As noted throughout this chapter, participants' level of prior knowledge of basic evolutionary concepts had a significant influence on the nature of their interactions with the simulation and with each other as they worked in small groups.
Chapter 10
Educational Implications

*If it is nothingness that awaits us, let us so act that it shall be an unjust fate* (Anonymous).

Educational Implications

Limitations of the Study. The results of the present investigation suggest that using a relatively simple computer simulation of basic evolutionary processes, in the context of small group discussions, can help participants with their understanding of some important biological concepts. This general conclusion, however, is limited by several factors. First, the sample size was relatively small. Recall, that the 19 participants who chose to be part of this investigation were from a class that was randomly selected from an original sample of 118 pre-service science teachers. With a much larger sample size, the analyses in this study that depended on separating individuals into high and low groups (e.g., the EKS and the ITEQ) could have been more trustworthy. A sample size of 60, for example, would have allowed for a more traditional split of the sample into thirds. This approach would have enabled greater confidence in any conclusions about disparity in knowledge when comparing the upper and lower thirds of the distribution.

Second, the relatively small sample size may have affected other aspects of the study as well. Recall that the groups that worked together for all phases of the study were formed on the basis of each participant's EKS score. It was originally hoped that each group could be composed of members from each third of the EKS distribution (i.e., bottom, middle, or upper). The relatively small number of participants did not allow for this kind of composition within groups. For example, two of the eight groups contained participants from the same third of the EKS distribution (i.e., the middle third). Also, these two groups and one other, did not have a participating member from the upper third of the EKS distribution. Thus, the limited sample size affected the composition of groups with respect to an important variable: level of knowledge about basic evolutionary concepts. In turn, this situation is likely to have affected the nature of the discussions in these groups and the ways in which some activities may have been conducted.

Although the sample size was small, the participants in this study were extremely enthusiastic, committed, and made themselves available for the various phases without
hesitation. However, in the context of participants' Bachelor of Education workloads, some of the tasks that they were asked to complete for this investigation may not have been given first priority. For example, despite having been provided with exemplary curriculum materials and almost nine weeks to complete their lesson plans on natural selection, all of the groups asked for a three day extension past the due date. Thus, many groups' lesson plans appeared to have been completed without participants having as much time to prepare them as they would have liked. As a result, there may have been a tendency for participants to err on the side of trying to do too many activities or of including too much under-researched information in an attempt to "cover the material". This would also have had an influence on the depth with which certain critical aspects of natural selection (e.g., level of selection, fitness, randomness, mutation, non-random elimination) were addressed. Furthermore, creating a single lesson on natural selection without knowing the context of how this lesson might fit into a unit on evolution may have affected its content and scope. Nonetheless, the limitations discussed here, and their effects on this study's results, are unlikely to be very much different from the constraints that operate on a teacher's day-to-day efforts in the classroom.

Another limitation of this study relates to the reliability, validity and practicality of the questionnaires. The EKS provided a reasonably accurate picture of participants' understanding of evolutionary concepts. However, it took most participants 40 minutes to answer its questions. Many participants commented that it was too long and that it required a great deal of effort to complete. An equally trustworthy version, but one that can be completed in 20 minutes, must be developed if a survey of this type is to become a practical research tool. Also, the NOSS provided a very interesting snapshot of participants' general science epistemological perspectives. However, some of the items may have lacked the necessary specificity and sensitivity that are needed to assess the subtleties of a construct as complicated as one's philosophy of science. As noted earlier, it may be that the NOSS's paper and pencil format captures a global perspective of one's views on the nature of science. From a research perspective, an alternative approach (e.g., interviews, critical instances) that examined specific details related to very narrow aspects of science epistemology could have led to more robust associations with the other constructs of interest in this study. Finding and/or creating a practical, easily administered assessment of an individual's views on the nature of science without being oppressively long or arduous would be a very challenging research task.
Another issue that could have been examined more closely pertains to the assumption of participants' prior knowledge of evolutionary concepts. As expected, this group of pre-service Intermediate/Senior science teachers reported taking a relatively large number of full-year biology courses ($\bar{x} = 4.1$, $sd = 2.5$). However, it turned out that the association between the number of university biology courses taken and one's understanding of basic evolutionary concepts was not as strong as was hoped. This assumption was a critical one because it had implications for the type of activities that participants engaged in while using the simulation and the kinds of questions that were posed to participants. In retrospect, a short information or "refresher" session (perhaps only an hour would have been needed) that introduced or reminded participants about basic evolutionary terminology and processes would have helped participants feel less overwhelmed by the simulation. Furthermore, a brief review may have provided participants with some of the necessary information that would have allowed them to make important connections among their observations of the simulation's objects and events (e.g., ants died, populations crashed), basic concepts (e.g., genotype, phenotype, mutation), and fundamental theoretical tenets of evolutionary theory (e.g., natural selection, fitness).

Another possible limitation of the study was related to the simulation itself. It is possible that the simulation's multimedia effects were too simple. Several participants mentioned that the program's graphics could have been improved. Given the apparent effectiveness of multimedia learning, some measure of realism (e.g., objects shaped like ants or simple sound effects) may have helped make certain objects and events more salient (e.g., which populations were thriving, when the anteater was attacking, the availability of food) or, could have reminded them of the importance of specific events (e.g., mating, fighting, sharing). All of these components could have helped to maintain participants' attention, and helped them to understand how to relate objects and events to the underlying mechanisms for their occurrence.

Finally, there were other aspects of the simulation's interface that could have been improved. For example, individual ant genotypes could be viewed by participants. However, users had to pause the simulation and then activate a separate screen to view the information. Although having this information is important, this process of switching screens detracted from the flow of using the simulation. The ideal situation would have been to allow users to obtain information about on-screen objects simply by using the
mouse pointer to select them. Today's object-oriented programming techniques allow for this level of interactivity and thus can provide an interface that would greatly enhance a user's ability to access critical information about the simulation.

Considering Science Pedagogy. The epistemological paradox discussed earlier requires some additional discussion. Recall that the paradox was described in terms of the way students and educators deal with scientific evidence in various domains of knowledge. For example, among primary and secondary teachers there is rarely any questioning of the models that comprise the theoretical foundations of chemistry and physics. It is difficult to find individuals who dismiss either the atomic theory of matter or the germ theory of disease as "just a theory". Ironically, evidence supporting the theory of evolution by natural selection is vastly more extensive and arguably much more compelling than many theories in science. The interesting question that arises from this paradox is, why do individuals tend to compartmentalize the ways in which they examine various truth claims made about the world? How do these individuals view the process of knowledge acquisition in the domain of science compared to other ways of learning about the world? Specifically, why do some individuals accept the atomic theory of matter or in the germ theory of disease and reject outright the theory of evolution by natural selection? What is the epistemic foundation for being data-driven and theory-bound in one domain while being ideologically-driven and atheoretical in another? Much in science education in general and for understanding evolution specifically depends on finding an answer to this question.

This paradox also raises the issue of who should be charged with the task of teaching evolution in high schools. As the findings from the Intentions to Teach Evolution Questionnaire revealed, it was possible to identify pre-service science teachers who are motivated and have the requisite knowledge to teach evolution effectively. Should science teachers be freed from the responsibility of teaching evolution if it contradicts their fundamental ideological commitments? If such world views mean that the topic will be taught perfunctorily, that how the theory might apply to humans will be ignored or that its role as the foundation of all biology will go unexamined, then it may be in the interest of all concerned to allow these teachers to forego such a responsibility. This approach will help to ensure that students receive instruction from teachers committed to an exploration of the material unconstrained by the epistemological paradox noted above. The argument of whether students should be freed from learning
evolutionary concepts because of ideological commitments follows the same line of reasoning. If there is a priori rejection of the theory because of a particular world view, then it is difficult to justify such a practice for what can arguably be seen, from the students' point of view, as attempts at indoctrination.

To acknowledge that it may be in the best interests of students to have some science teachers and not others teach evolutionary concepts may seem difficult to justify. However, educators are tacitly committed to just such an approach, for similar reasons, by hiring music teachers, French teachers or a physical education specialists. Why not science specialists? As domains in high school science become more and more complex, it may be that the system of teaching specialization currently in place at the university level may need to be applied at the high school level as well. As a minimum, it strongly suggests that teachers' strengths and weakness within and across domains should be acknowledged. Team teaching may be a useful first step in courses where such specialization or expertise is required.

Additionally, because the body of scientific knowledge in any domain is likely to change often, particularly in biology, this implies that teachers must be willing to engage in continuing education. Yet, the value and importance of AQ courses only becomes an issue when it is apparent that the quality of education that students receive in a given content domain is at risk. The data from this investigation justifiably suggest that if analogous levels of misconceptions in other subjects existed to the extent that they do regarding evolution, it would produce an immediate and assiduous remediation effort at all three educational levels. If the responsibility of educators is to "lead out of ignorance", then our efforts surrounding evolutionary theory reveal we are neither leading nor are we changing levels of ignorance. Darwin's idea will remain dangerous (Dennett, 1995) for all the reasons science educators putatively repudiate. Ironically, the paradox persists.

**Concluding Remarks.** Computer technology has provided educators with an approach to learning that is relatively new and is unprecedented in its potential to change the educational landscape. Computer simulations per se have been a large part of computing since its earliest days (Casti, 1997). However, simulations within mainstream educational institutions have become widely available only within the last 10 years or so.

What is not new on the educational front are the learners who will always bring to the learning situation a host of idiosyncratic ideas, beliefs, and attitudes. In science
education especially, because of the often counterintuitive nature of the subject matter, students' ideas about natural phenomena can be an obstacle to learning (Wolpert, 1993). Yet, many of these difficulties can be explored and may be remediated with relatively easy-to-perform laboratory exercises that provide students with hands-on, directly observable, replicable, empirical data that can be analyzed and examined for the purposes of connecting theory with observation. However, unlike any other topic in science, the problems associated with studying evolution cannot be remedied easily by lab activities. By definition, much of what evolution entails precludes useful observations even over a thousand human lifetimes. Aside from this constraint, the difficulties of studying and learning about evolution are often compounded by personal ideological commitments. Such commitments have made teaching about evolution problematic for science educators not just at the individual learner level but at the institutional and societal level.

The modest claim of this investigation is that a computer simulation of basic evolutionary process could be a valuable tool for learning about a concept that has proven to be quite intractable with traditional approaches. This tool can vary in sophistication from full-blown multimedia presentations to nothing more than coloured dots moving across the computer screen. Additionally, simulations can be used with students who have a broad range of abilities, background knowledge, and computing skills. The question that follows then is, where does the research go from here? Presented below is a list of major research topics that have the potential to advance our understanding of how students learn about evolution:

1. An investigation of the egocentric view of the world: Learners showed a tendency to be anthropomorphic and anthropocentric when discussing concepts.

2. An examination of the language students use to discuss concepts: Learners would use terms in the vernacular that when used in a domain-specific context, take on very different meanings.

3. An exploration of the retention of early intuitive ideas despite formal teaching: Some learners' understanding of some concepts seem particularly resistant to change.

4. An understanding of one's orientation and attitudes towards science: A learner's understanding and views on the nature of science are important factors in learning science concepts.
It may surprise the reader to learn that this list, although highly applicable, directly relevant, and easily derived as extensions of this study's results, was compiled nearly twenty years ago by Osborne and Gilbert (1980). These researchers were reporting a qualitative method that they were using that provided insight into students' ideas about specific physics concepts. The four themes noted above emerged as the elements most common and important in students' thinking regarding domain-specific content.

What is remarkable about the items in Osborne and Gilbert's (1980) list, and their direct relevance to this investigation, is their applicability to a wide variety of learning situations in science. The sheer stability and ubiquity of these themes over time strongly suggest two important considerations. First, the four themes remain an essential part of what is required for concept attainment not only in the study of evolution, but for science learning in general. Furthermore, implicit in the first three items is the idea that the pedagogical details of how best to implement a compensatory curriculum will require an intimate knowledge of a learner's idiosyncratic thoughts regarding the concepts in question. This understanding of students' subjective knowledge in the domain of evolution education is in its infancy relative to chemistry and physics (Good, 1994).

Methodological constraints aside, the difficulties participants appeared to have with the concept mapping task suggests the potential for a very straightforward curriculum intervention. Rather than starting with the individual pieces of evolutionary theory (e.g., adaptations, natural selection, genes), participants should perhaps start with a simplified version of "the big picture", like that depicted in Figure 14. This conceptual overview would provide a frame of reference from which participants could examine more specific facts and theoretical details. There is ample research evidence that such advanced organizers or scaffolding devices can help learners with concept attainment. Again, this is an example of the kind of learning support material that is easily incorporated into a computer-based learning program that uses a variety of learning activities including a simulation.

Second, the Osborne and Gilbert's (1980) list is significant for what it does not include. Specifically, their list makes no reference to those who are on the "front line" of the educational process, the teachers. The results from the current investigation suggest that changing students' understanding of evolution will have to start with changing teachers' understanding of evolution. Teachers will need to revisit their own background
knowledge and be critically reflective regarding what it is they do and do not know about evolution. There is virtually no research addressing high school teachers' knowledge of evolution and how this topic is implemented in Canadian schools. Teachers will also need to be aware of their own and their students' understanding of science as a way of knowing about the world and how this relates to their own epistemological and ideological commitments. This study raised such an awareness in several participants.

Figure 14. The concept map contained in the resources provided to participants (Adapted from Bishop and Anderson, 1990).

Traditional methods for learning about evolution will always have a place in the curriculum (e.g., McComas, 1994). However, the traditional materials (e.g., textbooks and associated activities) have their limitations. Teachers need access to a resource that avoids the potentially biased, often superficial treatment of the topic that is found in many of these materials (e.g., see Swarts et al., 1994 for a review of how evolution is treated in textbooks). Computer simulations of evolutionary processes are learning resources that are so versatile teachers can learn as much from their use as their students. What is lacking are well developed simulations that are accompanied by the kinds of support materials that will help learners at various stages of their understanding.

The beauty of simulations is that they allow students a "risk free" epistemological environment in which to explore models of evolutionary processes that are relatively unencumbered by the institutional constraints inherent in most textbooks' treatment of the topic. In other words, simulations may allow educators to circumvent the inherent biases found in most textbooks by examining evolutionary events as they might operate in the
real world. It would be important to know if this "process-oriented" approach could mitigate some of the constraints associated with teachers' and students' ideological commitments as they pertain to learning about the theory of evolution by natural selection. To paraphrase Kurt Lewin, there may be nothing so practical as a good simulation.
References


Appendix A

Evolution Knowledge Survey

Introduction

The purpose of this survey is to explore your understanding and ideas related to biological evolution. This not a test.

This questionnaire is divided into 5 sections. It should take about 35 minutes to complete all 5 sections. Instructions for how to complete each section are included before the questions for that section.

Background Information

Participant initials #: ________________________  Sex: □ Male  □ Female

My undergraduate degree is (please state your degree and major): ________________________

Please list all post-secondary Biology courses you have taken to date. If you cannot remember the exact title indicate the general theme of the course. Indicate whether the course was either a half term/1 semester or full year/2 semesters. Please list them in order in which you took them.

<table>
<thead>
<tr>
<th>Course Name or Theme</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>2) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>3) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>4) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>5) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>6) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>7) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>8) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>9) __________________</td>
<td>□ ½ term</td>
</tr>
<tr>
<td>10) __________________</td>
<td>□ ½ term</td>
</tr>
</tbody>
</table>

If you have any questions about any of the items please feel free to ask.
Section I

For each question, there are two parts: 'A' and 'B'.

For part 'A' of a question, CIRCLE a number (inside the arrow) which most closely corresponds to what you understand about evolution. Use the following scale when choosing your answer for part 'A' of a question.

<table>
<thead>
<tr>
<th>Statement on the left (e.g., The moon is made of rock)</th>
<th>1-The statement on the left is the only correct statement.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-The statement on the left is more correct.</td>
<td>3-Both statements are equally correct.</td>
</tr>
<tr>
<td>4-The statement on the right is more correct.</td>
<td>5-The statement on the right is the only correct statement.</td>
</tr>
<tr>
<td>1 2 3 4 5</td>
<td>Statement on the right (e.g., The moon is made of cheese).</td>
</tr>
</tbody>
</table>

If you think neither statement is correct, do not circle any number in the arrow and proceed to part (b).

Part b) Why did you choose this answer?

_________________________________________________________________

_________________________________________________________________

_________________________________________________________________

_________________________________________________________________

After choosing an answer for part 'A' proceed to part (b) of the question. For part (b), use a sentence or two to explain the reasons you chose your answer in part 'A'. It is important that in part (b) you try to provide an explanation for the answer you give in part 'A' of a question. If you don't have an answer for part (b) just write, "I don't know".
All questions in SECTION 1 of this survey are based on the evolution of ducks' feet.

Ducks are aquatic birds. Their feet are webbed and this trait makes them fast swimmers.

1a) The trait of webbed feet in ducks ...

| originally appeared in ducks or their ancestors because they lived in water and needed webbed feet to swim. | 1 - The statement on the left is the only correct statement. |
| | 2 - The statement on the left is more correct. |
| | 3 - Both statements are equally correct. |
| 4 - The statement on the right is more correct. |
| 5 - The statement on the right is the only correct statement. |

1b) Why did you choose this answer?

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

2a) While ducks were evolving webbed feet over a period of many generations ...

| with each generation, ducks had about the same amount of webbing on their feet as their parents. | 1 - The statement on the left is the only correct statement. |
| | 2 - The statement on the left is more correct. |
| | 3 - Both statements are equally correct. |
| 4 - The statement on the right is more correct. |
| 5 - The statement on the right is the only correct statement. |

2b) Why did you choose this answer?

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________

_________________________________________________________________________
3a) While ducks were evolving webbed feet …

<table>
<thead>
<tr>
<th>all ducks survived and reproduced at basically the same rate, regardless of the quantity of webbing on their feet.</th>
<th>1 - The statement on the left is the only correct statement.</th>
<th>those ducks without any webbing did not survive and reproduce at the same rate as those with some webbing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - The statement on the left is more correct.</td>
<td>3 - Both statements are equally correct.</td>
<td></td>
</tr>
<tr>
<td>4 - The statement on the right is more correct.</td>
<td>5 - The statement on the right is the only correct statement.</td>
<td></td>
</tr>
</tbody>
</table>

3b) Why did you choose this answer?

4a) The early ducks, or their ancestors, evolved webbed feet because …

<table>
<thead>
<tr>
<th>differences in webbing existed between them that enabled some to survive better than others.</th>
<th>1 - The statement on the left is the only correct statement.</th>
<th>the parents passed on genes that were modified due to environmental conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - The statement on the left is more correct.</td>
<td>3 - Both statements are equally correct.</td>
<td></td>
</tr>
<tr>
<td>4 - The statement on the right is more correct.</td>
<td>5 - The statement on the right is the only correct statement.</td>
<td></td>
</tr>
</tbody>
</table>

4b) Why did you choose this answer?
5a) Now that webbed feet are present in ducks ...

<table>
<thead>
<tr>
<th>there still exists considerable variation in the quantity of webbing in ducks' feet.</th>
<th>1 - The statement on the left is the only correct statement.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 - The statement on the left is more correct.</td>
</tr>
<tr>
<td></td>
<td>3 - Both statements are equally correct.</td>
</tr>
<tr>
<td></td>
<td>4 - The statement on the right is more correct.</td>
</tr>
<tr>
<td></td>
<td>5 - The statement on the right is the only correct statement.</td>
</tr>
</tbody>
</table>

5b) Why did you choose this answer?

6a) If a population of ducks were forced to live in a habitat where water was not present ...

<table>
<thead>
<tr>
<th>many ducks would die because their feet were poorly adapted to this environment.</th>
<th>1 - The statement on the left is the only correct statement.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2 - The statement on the left is more correct.</td>
</tr>
<tr>
<td></td>
<td>3 - Both statements are equally correct.</td>
</tr>
<tr>
<td></td>
<td>4 - The statement on the right is more correct.</td>
</tr>
<tr>
<td></td>
<td>5 - The statement on the right is the only correct statement.</td>
</tr>
</tbody>
</table>

6b) Why did you choose this answer?
7a) The populations of ducks evolved webbed feet because ...

<table>
<thead>
<tr>
<th>Statement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - The statement on the left is the only correct statement.</td>
<td></td>
</tr>
<tr>
<td>2 - The statement on the left is more correct.</td>
<td></td>
</tr>
<tr>
<td>3 - Both statements are equally correct.</td>
<td></td>
</tr>
<tr>
<td>4 - The statement on the right is more correct.</td>
<td></td>
</tr>
<tr>
<td>5 - The statement on the right is the only correct statement.</td>
<td></td>
</tr>
</tbody>
</table>

The ducks without webbed feet did not produce as many offspring that survived to adulthood as those ducks with some degree of webbed feet.

7b) Why did you choose this answer?

[Blank space for answer]
For questions 8-10 CIRCLE the letter beside the statement you believe to be the most correct and in the space provided, using a sentence or two, explain the reasons for your choice.

8) A number of mosquito populations are today resistant to DDT (a chemical used to kill insects), even though those species were not resistant to DDT when it was first introduced. Biologists believe that DDT resistance evolved in mosquitoes because:

A) Individual mosquitoes built up a resistance to DDT after being exposed to it. This resistance was then passed on to their offspring.

B) Mosquitoes needed to be resistant to DDT in order to survive.

C) A few mosquitoes were probably resistant to DDT before it was ever used.

D) Mosquitoes learned to adapt to their environment.

Why did you choose this answer?

9) Which of the following provides the best example of the process of evolutionary adaptation:

A) Fifty wild dogs successfully switch from hunting rabbits to mice because the rabbit population has become extinct. All 50 dogs survive the transition from rabbits to mice.

B) A large population (100) of dogs are able to produce heavy fur coats in a winter with severe cold and thus all are able to survive. All of these dogs' offspring have slightly heavier coats than their parents.

C) Due to extreme cold, half of a large dog population (100) dies. The other half survives and reproduces because their fur coats were heavier and better able to protect them from the weather.

D) A dog is moved to a warmer climate and responds by shedding large quantities of fur to help remain cool. The dog's offspring is born with a very heavy coat of fur, but is also able to shed the unneeded fur.

Why did you choose this answer?
10) As a population grows (think of a fish population, for example):

A) Each individual learns how to survive by finding new sources of food and other resources needed to live.

B) Uncontrolled, or unregulated, growth will lead eventually to many deaths because of a limit in natural resources.

C) Each generation will be more complex and reach a more perfect fit with the environment.

D) Each generation will produce fewer and fewer offspring to reduce the growth rate.

Why did you choose this answer?


11a) Please list the two most important kinds of evidence that you understand SUPPORTS the theory of evolution by natural selection. Please use a sentence or two to explain each of your answers.

Supportive Evidence # 1: __________________________________________________________

Supportive Evidence # 2: __________________________________________________________

11b) Please list the two most important kinds of evidence that you understand REFUTES the theory of evolution by natural selection. Please use a sentence or two to explain each of your answers.

Refuting Evidence # 1: __________________________________________________________

Refuting Evidence # 2: __________________________________________________________
Section III

Please CIRCLE the name of the lion from the list below that best answers the following question:

12) Biologists often use the term "fitness" when speaking of evolution. Below are descriptions of four male lions. According to your understanding of evolution, which lion would biologists consider the "fittest?"

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Lion Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size, Weight</td>
<td>George</td>
</tr>
<tr>
<td>3.2 m, 79.5 kgs.</td>
<td>2.7 m, 72.7 kgs.</td>
</tr>
<tr>
<td># of cubs fathered</td>
<td>19</td>
</tr>
<tr>
<td>Age at death</td>
<td>13 years</td>
</tr>
<tr>
<td>Reason cubs dies</td>
<td>4 cubs died due to malnutrition</td>
</tr>
<tr>
<td>Number of cubs surviving to adulthood</td>
<td>15</td>
</tr>
<tr>
<td>Comments</td>
<td>George is very large, very healthy. The strongest lion.</td>
</tr>
</tbody>
</table>

The fittest lion is: a) George  b) Ben  c) Spot  d) Sandy

In a sentence or two please explain the reasons for your answer:
Section IV

In 2 or 3 sentences, please answer the following questions.

13. Cheetahs (large African cats) are able to run faster than 100 km/hour when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 40 km/hour?

14. Cave salamanders are blind (they have eyes which are not functional). How would a biologist explain how blind cave salamanders evolved from sighted ancestors?

15. In a population of oak trees (all of the same species), some individuals have more offspring than others. Describe how this could affect the genetic evolution of the population.
There are two parts to each of the following questions (16A – 16K). For part (i) of a question, CIRCLE the number which most closely corresponds to what you understand about evolution. Use the numbered statements listed below each question to indicate your answer. For part (ii) of a question briefly explain why you chose your answer.

16A) Evolution is the process by which nature is improving itself over time. That is, there is a much better balance in nature today as compared to a thousand years ago.

(i)  
<table>
<thead>
<tr>
<th></th>
<th>The statement is correct</th>
<th>The statement is mostly correct</th>
<th>The statement is not completely correct</th>
<th>The statement is wrong</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(ii) Why did you choose this answer?
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

16B) The very delicate balance found in nature can not be explained simply by evolution. It must be controlled, at least in part, by some other forces.

(i)  
<table>
<thead>
<tr>
<th></th>
<th>The statement is correct</th>
<th>The statement is mostly correct</th>
<th>The statement is not completely correct</th>
<th>The statement is wrong</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(ii) Why did you choose this answer?
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

16C) Every specific structure on or in a living organism serves some purpose to help the organisms survive in nature.

(i)  
<table>
<thead>
<tr>
<th></th>
<th>The statement is correct</th>
<th>The statement is mostly correct</th>
<th>The statement is not completely correct</th>
<th>The statement is wrong</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(ii) Why did you choose this answer?
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
16D) If an organism has a need for some new physical structure, that structure will eventually materialize.

(i) The statement is correct
(ii) Why did you choose this answer?

16E) There exists in nature a hierarchy of living things. Humans are the most complex in function and are well adapted to their environment, while living things such as bacteria and mold are quite simple in function and are poorly adapted to their environment.

(i) The statement is correct
(ii) Why did you choose this answer?

16F) Evolution is too dependant on chance to explain everything found in nature. It might explain some minor events, like hair color or birth marks, but it surely can not account for extremely complex structures such as an eye or a brain.

(i) The statement is correct
(ii) Why did you choose this answer?
16G) Competition exists in nature, but still most organisms, such as birds and insects, eventually die of conditions related to old age.

(i) | 1 | The statement is correct | 2 | The statement is mostly correct | 3 | The statement is not completely correct | 4 | The statement is wrong |
---|---|----------------|---|----------------|---|----------------|---|----------------|

(ii) Why did you choose this answer?

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

16H) Because of evolution, each new generation is a little more complex and better adapted than their parents.

(i) | 1 | The statement is correct | 2 | The statement is mostly correct | 3 | The statement is not completely correct | 4 | The statement is wrong |
---|---|----------------|---|----------------|---|----------------|---|----------------|

(ii) Why did you choose this answer?

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________

16I) In the past 100,000 years, all living things have evolved, with the significant exception of humans.

(i) | 1 | The statement is correct | 2 | The statement is mostly correct | 3 | The statement is not completely correct | 4 | The statement is wrong |
---|---|----------------|---|----------------|---|----------------|---|----------------|

(ii) Why did you choose this answer?

________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
________________________________________________________________________
16J) If scientists could observe and understand all the biological and geological evidence, they would conclude that evolution does not exist.

(i)  The statement is correct

The statement is mostly correct

(ii) Why did you choose this answer?

16K) Evolution should not be taught in public schools because not enough is known about it and also because it contradicts many people's religious beliefs.

(i)  The statement is correct

The statement is mostly correct

(ii) Why did you choose this answer?

Section V

17. Do you believe Charles Darwin's theory of evolution by natural selection to be true? (CIRCLE one)

Yes     No     Maybe     In part     I don't know

Please explain your answer?
Appendix B

Nature of Science Survey - Part A

Please complete the following items:

1) Participant Initials #: ______________________  
2) Gender: □ Female □ Male

3) Please list all your teachable subjects:
   a) __________________________
   b) __________________________
   c) __________________________
   d) __________________________

4) Email address: __________________________

INSTRUCTIONS

Each question begins with a statement about a science-technology-society topic. Most of these statements express an extreme view on the topic. You may happen to agree strongly with this view; you may happen to disagree vigorously; or your own position may be in between the two.

Next, there is a list of positions (or viewpoints) on the issue. These usually go from one extreme to the other. You are asked to choose one of these positions, BUT ONLY ONE – the one that comes closest to your personal view or belief.

To summarize:
   • Read each statement carefully.
   • Think to yourself whether you agree or disagree with the statement, or can’t make up your mind.
   • Then read the list of different positions on the topic.
   • Pick the one that comes closest to your own position and CIRCLE the letter beside the statement.

Each statement ends with the same two positions. Here is how you can use them if you wish:

“I don’t understand.” This choice is included in case there is a key word or phrase that you just don’t understand.

OR

“I don’t know enough about this subject to make a choice.”

There are no “right” answers; this is NOT a test. We simply want to understand what your position is on a number of issues about science and about how it relates to technology and society.

There are 20 items in total. Do not spend too much time on any one question. It should take about 30 minutes to complete Part ‘A’ of this survey.
1. Scientific observations made by competent scientists will usually be different if the scientists believe different theories.

Your position, basically: (Please read from A to G and then choose one.)

A. Yes, because scientists will experiment in different ways and will notice different things.
B. Yes, because scientists will think in different ways and will alter their observations.
C. Scientific observations will not differ very much even though scientists believe different theories. If the scientists are indeed competent their observations will be similar.
D. No, because observations are as exact as possible. This is how science has been able to advance.
E. No, observations are exactly what we see and nothing more; they are the facts.
F. I don't understand.
G. I don't know enough about this subject to make a choice.

2. Many scientific models used in research laboratories (such as the model of heat, the neuron, DNA, or the atom) are copies of reality.

Your position, basically: (Please read from A to I and then choose one.)

Scientific models ARE copies of reality:

A. because scientists say they are true, so they must be true.
B. because much scientific evidence has proven them true.
C. because they are true to life. Their purpose is to show us reality or teach us something about it.
D. Scientific models come close to being copies of reality, because they are based on scientific observations and research.

Scientific models are NOT copies of reality:

E. because they are simply helpful for learning and explaining, within their limitations.
F. because they change with time and with the state of our knowledge, like theories do.
G. because these models must be ideas or educated guesses, since you can't actually see the real thing.
H. I don't understand.
I. I don't know enough about this subject to make a choice.
3. When scientists classify something (for example, a plant according to its species, an element according to the periodic table, energy according to its source, or a star according to its size), scientists are classifying nature according to the way nature really is; any other way would simply be wrong.

Your position, basically: (Please read from A to H and the choose one.)

A. Classifications match the way nature really is since scientists have proven them over many years of work.
B. Classifications match the way nature really is since scientists use observable characteristics when they classify.
C. Scientists classify nature in the most simple and logical way, but their way isn't necessarily the only way.
D. There are many ways to classify nature, but agreeing on one universal system allows scientists to avoid confusion in their work.
E. There could be other correct ways to classify nature because science is liable to change and new discoveries may lead to different classifications.
F. Nobody knows the way nature really is. Scientists classify nature according to their perceptions or theories. Science is never exact, and nature is so diverse. Thus, scientists could correctly use more than one classification scheme.

G. I don't understand.
H. I don't know enough about this subject to make a choice.

4. Even when scientific investigations are done correctly, the knowledge that scientists discover from those investigations may change in the future.

Your position, basically: (Please read from A to F and then choose one.)

Scientific knowledge changes:

A. because new scientists disprove the theories or discoveries of old scientists. Scientists do this by using new techniques or improved instruments, by finding new factors overlooked before or by detecting errors in the original "correct" investigation.
B. because the old knowledge is reinterpreted in light of new discoveries. Scientific facts can change.
C. Scientific knowledge APPEARS to change because the interpretation or the application of the old facts can change. Correctly done experiments yield unchangeable facts.
D. Scientific knowledge APPEARS to change because new knowledge is added on to old knowledge; the old knowledge doesn't change.

E. I don't understand.
F. I don't know enough about this subject to make a choice.
5. When developing new theories or laws, scientists need to make certain assumptions, about nature (for example, matter is made up of atoms). These assumptions must be true in order for science to progress properly.

Your position, basically: (Please read from A to H and then choose one.)

Assumptions MUST be true in order for science to progress:

A. because correct assumptions are needed for correct theories and laws. Otherwise scientists would waste a lot of time and effort using wrong theories and laws.
B. otherwise society would have serious problems, such as inadequate technology and dangerous chemicals.
C. because scientists do research to prove their assumptions true before going on with their work.
D. It depends. Sometimes science needs true assumptions in order to progress. But sometimes history has shown that great discoveries have been made by disproving a theory and learning from its false assumptions.
E. It doesn't matter. Scientists have to make assumptions, true or not, in order to get started on a project. History has shown that great discoveries have been made by disproving a theory and learning from its false assumptions.
F. Scientists do not make assumptions. They research an idea to find out if the idea is true. They don't assume it is true.
G. I don't understand.
H. I don't know enough about this subject to make a choice.

6. In reaction to Einstein's equation, \( E = mc^2 \), scientists said, "Such a beautifully elegant equation must be a true description of nature." This quotation shows that scientists assume their equations or ideas should match the elegance of nature.

Your position, basically: (Please read from A to H, and then choose one.)

Scientists ASSUME their ideas should be elegant:
A. in order to be true to nature. Scientists know that nature is beautiful or elegant if looked at in the correct way.
B. because scientific ideas should be simple, consistent, and logical. Nature's elegance has nothing to do with it.
C. the elegance of scientific ideas is due to the fact that scientists worked long and hard to produce them and so the scientists find the ideas elegant. Nature's elegance has nothing to do with it.
D. although scientists may feel that nature is beautiful or elegant.
E. because scientists know that not everything in nature is beautiful or elegant.
F. because scientists know that everyone sees elegance differently

G. I don't understand.
H. I don't know enough about this subject to make a choice.
7. Good scientific theories explain observations well. But good theories are also simple rather than complex.

Your position, basically: (Please read from A to H and then choose one.)

A. good theories are simple. The best language to use is simple, short, direct language.
B. it depends on how deeply you want to get into explanation. A good theory can explain something either in a simple way or a complex way.
C. it depends on the theory. Some good theories are simple, some are complex.
D. good theories can be complex, but they must be able to be translated into simple language if they are going to be used.
E. theories are usually complex. Some things cannot be simplified if a lot of details are involved.
F. Most good theories are complex. If the world was simple, theories could be simpler.

G. I don't understand.
H. I don't know enough about this subject to make a choice.

8. When scientists investigate, it is said that they follow the scientific method. The scientific method is:

Your position, basically: (Please read from A to L and then choose one.)

A. the lab procedures or techniques; often written in a book or journal, and usually by a scientist.
B. recording your results carefully.
C. controlling experimental variables carefully, leaving no room for interpretation.
D. getting facts, theories or hypotheses efficiently.
E. testing and retesting -- proving something true or false in a valid way.
F. postulating a theory then creating an experiment to prove it.
G. questioning, hypothesizing, collecting data and concluding.
H. a logical and widely accepted approach to problem solving.
I. an attitude that guides scientists in their work.
J. considering what scientists actually do, there really is no such thing as the scientific method.

K. I don't understand.
L. I don't know enough about this subject to make a choice.
9. The best scientists are those who follow the steps of the scientific method.

Your position, basically: (Please read from A to G and then choose one.)

A. the scientific method ensures valid, clear, logical and accurate results. Thus, most scientists will follow the steps of the scientific method.
B. the scientific method should work well for most scientists; based on what we learned in school.
C. the scientific method is useful in many instances, but it does not ensure results. Thus, the best scientists will also use originality and creativity.
D. the best scientists are those who use any method that might get favourable results (including the method of imagination and creativity).
E. many scientific discoveries were made by accident, and not by sticking to the scientific method.

F. I don't understand.
G. I don't know enough about this subject to make a choice.

10. Scientific discoveries occur as a result of a series of investigations, each one building on and earlier one, and each one leading logically to the next one, until the discovery is made.

Your position, basically: (Please read from A to I and then choose one.)

A. because experiments (e.g., the experiments that led to the model of the atom, or discoveries about cancer) are like laying bricks onto a wall.
B. because research begins by checking the results of an earlier experiment to see if it is true. A new experiment will be checked by the people who come afterwards.
C. usually scientific discoveries result from a logical series of investigations. But science is not completely logical. There is an element of trial and error, hit and miss, in the process.
D. Some scientific discoveries are accidental, or they are the unpredicted product of the actual intention of the scientist. However, more discoveries result from a series of investigations building logically one upon the other.
E. most scientific discoveries are accidental, or they are the unpredicted product of the actual intention of the scientist. Some discoveries result from a series of investigations building logically one upon the other.

Scientific discoveries do not occur as a result of a logical series of investigations:
F. because discoveries often result from the piecing together of previously unrelated bits of information
G. because discoveries occur as a result of a wide variety of studies which originally had nothing to do with each other, but which turned out to relate to each other in unpredictable ways.

H. I don't understand.
I. I don't know enough about this subject to make a choice.
11. Scientists publish the results of their work in scientific journals. When scientists write an article for a journal, they organize their report in a very logical orderly way. However, scientists actually do the work in a much less logical way.

Your position, basically: (Please read from A to I and then choose one.)

Articles are written in a more logical way than the actual work:
A. because scientists can think and work without following a set plan. Consequently, if you read the actual order of their thoughts and procedures, it would be confusing. Therefore, scientists write logically so other scientists will understand the results.
B. because scientific hypotheses are personal views or guesses and thus are not logical. Scientists, therefore, write logically so other scientists will understand the results.
C. scientists usually don't want to give away "the recipe" but they do want to tell the world about their results. So they write it up logically but in a way that does not reveal how it was actually done.
D. it depends. Sometimes scientific discoveries happen by accident. But other times discoveries happen in a logical orderly way, just like the articles are written.

Articles are written in a logical way showing how the actual work was done:
E. because a scientist's work is conducted logically; otherwise, it would not be useful to science and technology.
F. because scientists do work in a logical way so that their published report will be easier to write in a logical way.
G. articles are not necessarily written in a logical way. They're written the way the work was done. This can be complicated or straightforward.

H. I don't understand.
I. I don't know enough about this subject to make a choice.

12. Scientists should NOT make errors in their work because these errors slow the advance of science.

Your position basically: (Please read from A to G and then choose one.)

A. errors slow the advance of science. Misleading information can lead to false conclusions. If scientists don't immediately correct the errors in their results, then science is not advancing.
B. errors slow the advance of science. New technology and equipment reduce errors by improving accuracy and so science will advance faster.

Errors CANNOT be avoided:
C. so scientists reduce errors by checking each others results until agreement is reached.
D. some errors can slow the advance of science, but other errors can lead to a new discovery or breakthrough. If scientists learn from their errors and correct them, science will advance.
E. Errors most often help the advance of science. Science advances by detecting and correcting the errors of the past.

F. I don't understand.
G. I don't know enough about this subject to make a choice.
13. Even when making predictions based on accurate knowledge, scientists and engineers can tell us only what *probably* might happen. They cannot tell what will happen for certain.

Your position, basically: (Please read from A to G and then choose one.)

A. because there is always room for error and unforeseen events which will affect a result. No one can predict the future for certain.
B. because accurate knowledge changes as new discoveries are made, and therefore predictions will always change.
C. because a prediction is not a statement of fact. It is an educated guess.
D. because scientists *never* have all the facts. Some data are always missing.
E. it depends. Predictions are certain, only as long as there is accurate knowledge and enough information.
F. I don't understand.
G. I don't know enough about this subject to make a choice.

14. Even when people use mathematics accurately in science and engineering, they can only predict what will probably happen. The can never conclude with 100% certainty.

Your position, basically: (Please read from A to F and then choose one.)

A. because there is always measurement error or human error.
B. because there are always unknown or unforeseen events which will affect a result
C. predictions with mathematics are *usually* 100% certain, because they are based on tested results.
D. predictions with mathematics are *always* 100% certain, because mathematics itself is certain.
E. I don't understand.
F. I don't know enough about this subject to make a choice.
15. If scientists find that people working with asbestos have twice as much chance of getting lung cancer as the average person, this must mean that asbestos causes lung cancer.

Your position, basically: (Please read from A to G and then choose one.)

A. the facts obviously prove that asbestos causes lung cancer. If asbestos workers have a greater chance of getting lung cancer, then asbestos is the cause.

The facts do NOT necessarily mean that asbestos causes lung cancer:
B. because more research is needed to find out whether it is asbestos or some other substance that causes the lung cancer.
C. because asbestos might work in combination with other things, or may work indirectly (e.g., weakening your resistance to other things which cause you to get lung cancer).
D. because if it did, all asbestos workers would have developed lung cancer.
E. asbestos cannot be the cause of lung cancer because many people who don’t work with asbestos also get lung cancer.

F. I don't understand.
G. I don’t know enough about this subject to make a choice.

16. Science rests on the assumption that the natural world can not be altered by a supernatural being (for example, a deity).

Your position, basically: (Please read from A to G and then choose one.)

Scientists assume that a supernatural being will NOT alter the world:
A. because the supernatural is beyond scientific proof. Other views, outside the realm of science, may assume that a supernatural being can alter the natural world.
B. because if a supernatural being did exist, scientific facts could change in the wink of an eye. BUT scientists repeatedly get consistent results.
C. it depends. What scientists assume about a supernatural being is up to the individual scientist.
D. anything is possible. Science does not know everything about nature. Therefore, science must be open-minded to the possibility that a supernatural being could alter the natural world.
E. science can investigate the supernatural and can possibly explain it. Therefore, science can assume the existence of supernatural beings.

F. I don't understand.
G. I don’t know enough about this subject to make a choice.
17. For this statement, assume that a gold miner "discovers" gold, while an artist "invents" a sculpture. Some people think that scientists *discover* scientific **LAWS**. Others think that scientists *invent* them. What do you think?

Your position, basically: (Please read from A to G and then choose one.)

Scientists **discover** scientific laws:
A. because the laws are out there in nature and scientists just have to find them.
B. because laws are based on **experimental facts**.
C. but scientists invent the **methods** to find those laws.
D. some scientists may stumble onto a law by chance, thus discovering it. But other scientists may invent the law from the facts they already know.
E. scientists **invent** laws, because scientists interpret the experimental fact which they discover. Scientists don't invent what nature does, but they do invent the laws which **describe** what nature does.

F. I don't understand.
G. I don't know enough about this subject to make a choice.

18. For this statement, assume that a gold miner "discovers" gold, while an artist "invents" a sculpture. Some people think that scientists *discover* scientific **HYPOTHESES**. Others think that scientists *invent* them. What do you think?

Your position, basically: (Please read from A to H and then choose one.)

Scientists **discover** a hypothesis:
A. because the idea was there all the time to be uncovered.
B. because it is based on **experimental facts**.
C. but scientists invent the **methods** to find the hypothesis.
D. some scientists may stumble onto a hypothesis by chance, thus discovering it. But other scientists may invent the hypothesis from facts they already know.

Scientists **invent** a hypothesis:
E. because a hypothesis is an interpretation of experimental **facts** which scientists have discovered.
F. because inventions (hypotheses) come from the mind -- we create them.

G. I don't understand.
H. I don't know enough about this subject to make a choice.
19. For this statement, assume that a gold miner "discovers" gold, while an artist "invents" a sculpture. Some people think that scientists discover scientific THEORIES. Others think that scientists invent them. What do you think?

Your position, basically: (Please read from A to G and then choose one.)

Scientists discover a theory:
A. because the idea was there all the time to be uncovered.
B. because it is based on experimental facts.
C. but scientists invent the methods to find the theories.
D. some scientists may stumble onto a theory by chance, thus discovering it. But other scientists may invent the theory from facts they already know.

Scientists invent a theory:
E. because a theory is an interpretation of experimental facts which scientists have discovered.
F. because inventions (theories) come from the mind -- we create them.

F. I don't understand.
G. I don't know enough about this subject to make a choice.

----------------------------------------

20. Scientists in different fields look at the same thing from very different points of view (e.g., H+ causes chemists to think of acidity and physicists to think of protons). This makes it difficult for scientists in different fields to understand each other's work.

Your position, basically: (Please read from A to G and then choose one.)

It is difficult for scientists in different fields to understand each other:
A. because scientific ideas depend on the scientist's viewpoint or on what the scientist is used to.
B. because scientists must make an effort to understand the language of other fields which overlaps with their own field.

It is fairly easy for scientists in different fields to understand each other:
C. because scientists are intelligent and so they can find ways to learn the different languages and points of view of another field.
D. because they have likely studied the various fields at one time.
E. because scientific ideas overlap from field to field. Facts are facts no matter what the scientific field is.

F. I don't understand.
G. I don't know enough about this subject to make a choice.
Nature of Science Survey - Part B

This survey is intended to identify your present position with respect to several aspects related to the practices of science and technology.

Read each of the statements below carefully, and assign each statement a number between -5 and +5 where "-5" means you strongly disagree with the statement, while "+5" means you strongly agree with the statement. If you assign the statement a "0", that means you believe it is equally, or sometimes true and sometimes false. As a visual guide, you might use the scale below.

<table>
<thead>
<tr>
<th>Degree of Agreement</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5</td>
</tr>
<tr>
<td>Strongly Disagree</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statements</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) The results that pupils get from their experiments are as valid as anybody else's</td>
<td>[___]</td>
</tr>
<tr>
<td>2) Science is essentially a masculine construct</td>
<td>[___]</td>
</tr>
<tr>
<td>3) Science facts are what scientists agree they are</td>
<td>[___]</td>
</tr>
<tr>
<td>4) Scientists expect, eventually, fully reveal reality</td>
<td>[___]</td>
</tr>
<tr>
<td>5) Scientists have no idea of the outcome of an experiment before they do it</td>
<td>[___]</td>
</tr>
<tr>
<td>6) Scientific research is economically and politically determined</td>
<td>[___]</td>
</tr>
<tr>
<td>7) Science education should be more about the learning of scientific processes than the learning of scientific laws, theories and inventions</td>
<td>[___]</td>
</tr>
<tr>
<td>8) The processes of science are divorced from moral and ethical considerations</td>
<td>[___]</td>
</tr>
<tr>
<td>9) The most valuable part of a science education is what remains after the laws, theories and inventions have been forgotten</td>
<td>[___]</td>
</tr>
<tr>
<td>10) Scientific theories are valid if they work</td>
<td>[___]</td>
</tr>
<tr>
<td>11) Science proceeds by drawing generalizable conclusions (laws and theories) from the available data</td>
<td>[___]</td>
</tr>
<tr>
<td>12) Most widely-accepted theories are very close to the truth</td>
<td>[___]</td>
</tr>
<tr>
<td>13) Human emotions play no part in the creation of scientific knowledge</td>
<td>[___]</td>
</tr>
<tr>
<td>14) Scientific theories usually describe a real external world which is independent of human perception</td>
<td>[___]</td>
</tr>
<tr>
<td>15) A good solid grounding in basic scientific laws, theories and inventions is essential before young scientists (e.g., students) can go on to make discoveries of their own</td>
<td>[___]</td>
</tr>
<tr>
<td>16) Scientific theories have changed over time simply because experimental techniques and devices have improved</td>
<td>[___]</td>
</tr>
<tr>
<td>17) The methods of science can be transferred from one scientific investigation to another</td>
<td>[___]</td>
</tr>
<tr>
<td>18) In practice, choices between competing theories are made purely on the basis of experimental results</td>
<td>[___]</td>
</tr>
<tr>
<td>19) Scientific theories are as much a result of imagination and intuition as inference (concluding) from experimental results</td>
<td>[___]</td>
</tr>
<tr>
<td>20) Scientific knowledge deserves higher status than other kinds of knowledge</td>
<td>[___]</td>
</tr>
<tr>
<td>21) There are certain physical events in the universe which science cannot explain</td>
<td>[___]</td>
</tr>
<tr>
<td>22) Scientific knowledge is morally neutral; only the application of the knowledge is ethically determined</td>
<td>[___]</td>
</tr>
<tr>
<td>23) All scientific experiments and observations are determined by existing theories</td>
<td>[___]</td>
</tr>
<tr>
<td>24) Science is essentially characterized by the methods and processes it uses</td>
<td>[___]</td>
</tr>
</tbody>
</table>
Appendix C

Intentions to Teach Evolution Questionnaire

A Questionnaire About Teaching Biological Concepts
This survey is designed to explore your attitudes and beliefs regarding teaching evolution by natural selection. It is NOT a test; there are no right answers so please try to answer honestly. This questionnaire should take you approximately 15 minutes to complete.

The questionnaire is divided into 3 pairs of related sections.

Sections 1 & 2
Section 1 asks you to indicate the Likelihood that certain outcomes could occur as a result of you teaching evolution by natural selection with your students.

Section 2 asks you to Evaluate those outcomes mentioned in section 1 along several different dimensions (e.g., good/bad, beneficial/harmful, valuable/worthless, useful/useless, etc.)

Sections 3 & 4
Section 3 asks you to indicate the Likelihood that certain individuals or groups could be influential in your decision to teach the theory of evolution by natural selection with your students.

Section 4 asks you to indicate the Likelihood that you actually would be motivated by those individuals or groups mentioned in section 3 to do as they would like.

Sections 5 & 6
Section 5 asks you to indicate the Likelihood that you could influence whether you taught the theory of evolution by natural selection.

Section 6 asks you to indicate the Likelihood that the outcomes mentioned in section 5 would actually occur.

Please try to answer ALL questions. Incomplete questionnaires can be difficult to interpret.

If you have any questions as you go along, please feel free to ask for assistance.
SECTION 1, page 1: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that each of the outcomes or results listed could occur if you were to teach your students about the theory of evolution by natural selection.

<table>
<thead>
<tr>
<th>LIKELIHOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
</tr>
<tr>
<td>+2</td>
</tr>
<tr>
<td>+1</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-1</td>
</tr>
<tr>
<td>-2</td>
</tr>
<tr>
<td>-3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTCOME/RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) could help them to understand ideas about the nature of science.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>2) could offend some of them.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>3) could help them appreciate why there is such a diversity of life forms on the planet.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>4) could create a lot of controversy in the class.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>5) could be a way to show them how theories can be used in science.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>6) could be a way to help them learn about important people and events in the history of science.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>7) could be difficult for me because of my religious beliefs.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>8) could end up confusing most of them.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>9) could help them learn about other aspects of Biology.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>10) could help them learn about genetics.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
<tr>
<td>11) could help promote critical thinking.</td>
</tr>
<tr>
<td>+3 +2 +1 0 -1 -2 -3</td>
</tr>
</tbody>
</table>
SECTION 1, page 2: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that each of the outcomes or results listed could occur if you were to teach your students about the theory of evolution by natural selection.

<table>
<thead>
<tr>
<th>LIKELIHOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
</tr>
<tr>
<td>extremely likely</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OUTCOME/RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12) could help them see how evidence is used in science.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>13) could help them to understand some of the reasons behind human behaviour.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>14) could help them to understand adaptations and how they can emerge in a population of organisms.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>15) could end up upsetting a lot of people.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>16) could provide a way to integrate many other subjects into science lessons like Mathematics, Reading, English, and other subjects.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>17) could provide insight into human development.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>18) could lead to conflict in the science department at my school.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>19) could help them to understand why some species go extinct.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>20) could help them understand why some antibiotics have become less effective against certain kinds of bacteria.</td>
</tr>
<tr>
<td>+3</td>
</tr>
<tr>
<td>21) could help them to understand human brain functioning and cognition.</td>
</tr>
<tr>
<td>+3</td>
</tr>
</tbody>
</table>
SECTION 2, page 1: For each of the statements below CIRCLE the number that corresponds to your EVALUATION of the outcomes or results that you responded to in section 1.

**EVALUATION of OUTCOME/RESULTS**

<table>
<thead>
<tr>
<th>Evaluation of Outcome/Result</th>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) could help them to understand ideas about the nature of science, then this would be</td>
<td>extremely quite</td>
<td>valuable</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>2) could offend some of them, then this would be</td>
<td>extremely quite</td>
<td>good</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>3) could help them appreciate why there is such a diversity of life forms on the planet, then this would be</td>
<td>extremely quite</td>
<td>useful</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>4) creates a lot of controversy in the class, then this would be</td>
<td>extremely quite</td>
<td>beneficial</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>5) could be a way to show them how theories can be used in science, then this would be</td>
<td>extremely quite</td>
<td>valuable</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>6) could be a way to help them learn about important people and events in the history of science, then this would be</td>
<td>extremely quite</td>
<td>useful</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>7) was difficult for me because of my religious beliefs, then this would be</td>
<td>extremely quite</td>
<td>good</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>8) could end up just confusing most of them, then this would be</td>
<td>extremely quite</td>
<td>beneficial</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>9) could help them learn about other aspects of Biology, then this would be</td>
<td>extremely quite</td>
<td>useful</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
<tr>
<td>10) could help them learn about genetics, then this would be</td>
<td>extremely quite</td>
<td>valuable</td>
<td>slightly</td>
<td>neither</td>
<td>slightly</td>
<td>quite</td>
<td>extremely</td>
</tr>
</tbody>
</table>
SECTION 2, page 2: For each of the statements below CIRCLE the number that corresponds to your EVALUATION of the outcomes or results that you responded to in section 1.

EVALUATION of OUTCOME/RESULTS

11) could help promote critical thinking, then this would be
   
   -3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   useful useful useful useless useless useless

12) could help them see how evidence is used in science, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   useful useful useful useless useless useless

13) could help them to understand some of the reasons behind human behaviour.
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   valuable valuable valuable worthless worthless worthless

14) could help them to understand adaptations and how they can emerge in a population
   of organisms, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   useful useful useful useless useless useless

15) could end up just upsetting a lot of people, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   beneficial beneficial beneficial harmful harmful harmful

16) could provide a way to integrate many other subjects into science lessons like
   mathematics, reading, English, and other subjects, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   beneficial beneficial beneficial harmful harmful harmful

17) could provide insight into human development.
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   valuable valuable valuable worthless worthless worthless

18) could lead to conflict in the science department at my school, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   good good good bad bad bad

19) could help them to understand why some species go extinct, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   useful useful useful useless useless useless

20) could help them understand why some antibiotics have become less effective
   against certain kinds of bacteria, then this would be
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   beneficial beneficial beneficial harmful harmful harmful

21) help them to understand human brain functioning and cognition.
   
   +3 +2 +1 0 -1 -2 -3
   extremely quite slightly neither slightly quite extremely
   valuable valuable valuable worthless worthless worthless
SECTION 3, page 1: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that certain individuals or groups could be influential in your decision to teach the theory of evolution by natural selection with your students.

<table>
<thead>
<tr>
<th>LIKELIHOOD</th>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>neither</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>extremely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>likely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>likely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>likely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>unlikely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Influential individuals or groups

1) Other teachers in my science department could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

2) My students' parents could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

3) My religious organization could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

4) My friends could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

5) The principal at my school could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

6) My school board could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3

7) The students themselves could be influential in my decision to teach the theory of evolution by natural selection.
   +3  +2  +1  0  -1  -2  -3
SECTION 4, page 1: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that you actually would be motivated by those individuals or groups mentioned in section 3 to do as they would like.

<table>
<thead>
<tr>
<th>LIKELIHOOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>+3</td>
</tr>
<tr>
<td>extreme</td>
</tr>
<tr>
<td>likely</td>
</tr>
</tbody>
</table>

Motivational influence of individuals or groups

1) generally, I would want to do what most of the other teachers in my science department felt was important to do.
   +3  +2  +1  0  -1  -2  -3

2) generally, I would want to do what my students' parents felt was important to do.
   +3  +2  +1  0  -1  -2  -3

3) generally, I would want to do what my religious organization felt was important to do.
   +3  +2  +1  0  -1  -2  -3

4) generally, I would want to do what my friends felt was important for me to do.
   +3  +2  +1  0  -1  -2  -3

5) generally, I would want to do what the principal at my school felt was important for me to do.
   +3  +2  +1  0  -1  -2  -3

6) generally, I would want to do what my school board felt was important for me to do.
   +3  +2  +1  0  -1  -2  -3

7) generally, I would want to do what my students themselves felt was important for me to do.
   +3  +2  +1  0  -1  -2  -3
SECTION 5, page 1: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that each item could influence your decision to teach the theory of evolution by natural selection with your students.

### LIKELIHOOD

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely likely</td>
<td>quite likely</td>
<td>slightly likely</td>
<td>neither likely nor unlikely</td>
<td>slightly unlikely</td>
<td>quite unlikely</td>
<td>extremely unlikely</td>
</tr>
</tbody>
</table>

### Influence over outcome/results

1) Not having a well developed curriculum and lesson plans will prevent me in teaching my students the theory of evolution by natural selection.

   +3 +2 +1 0 -1 -2 -3

2) Whether or not I teach the theory of evolution by natural selection with my students will be pretty much up to me.

   +3 +2 +1 0 -1 -2 -3

3) I'm going to rely on whatever textbooks are available for the unit I develop to assist me with teaching my students the theory of evolution by natural selection.

   +3 +2 +1 0 -1 -2 -3

4) There are going to be many factors that are beyond my control that could affect my decision to teach my students the theory of evolution by natural selection.

   +3 +2 +1 0 -1 -2 -3

5) The courses I've taken in university have provided me with the background I need to teach my students the theory of evolution by natural selection.

   +3 +2 +1 0 -1 -2 -3

6) If my students decide they don't want me to teach the theory of evolution by natural selection, I'll probably just skip over that unit in my science course.

   +3 +2 +1 0 -1 -2 -3

7) If pressed for time in trying to cover all the material in a unit, teaching the theory of evolution by natural selection would be fairly high on the list of things I would choose to skip over.

   +3 +2 +1 0 -1 -2 -3
SECTION 6, page 1: For each of the statements below CIRCLE the number that corresponds to the LIKELIHOOD that each event could actually occur as it pertains to you teaching the theory of evolution by natural selection with your students.

<table>
<thead>
<tr>
<th>LIKELIHOOD</th>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>extremely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>neither</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slightly</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>quite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>extremely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Chance of an outcome/results**

1) The chance of not having a well developed curriculum and lesson plans that I could use in teaching the theory of evolution by natural selection is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

2) The chance of whether it will solely be my decision that I teach the theory of evolution by natural selection with my students is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

3) The chance that I will rely on whatever textbooks are available for the unit I develop to assist me with teaching my students the theory of evolution by natural selection is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

4) The chance that there are going to be many factors that are beyond my control that could affect my decision to teach my students the theory of evolution by natural selection is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

5) The chance that my university courses provided the background I need to teach the theory of evolution by natural selection is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

6) The chance that I'll skip over a unit on evolution by natural selection if my students decide they don't want me to teach it is

<table>
<thead>
<tr>
<th>+3</th>
<th>+2</th>
<th>+1</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-3</th>
</tr>
</thead>
</table>

7) If pressed for time in trying to cover all the material in a unit, the chance that I would skip over teaching the theory of evolution by natural selection is

| +3 | +2 | +1 | 0  | -1 | -2 | -3 |
Appendix D

Your Initials: _______ Resource Use Survey

Instructions
Throughout this study you used a variety of resources related to evolution by natural selection. You may have found some of these resources more useful or helpful than others; some you may not have even consulted. The following statements ask you to rate the overall usefulness of these resources.

Below is a list of the major resources you may have used in this study. For each pair listed, place a check mark in the box under the resource that you found MOST USEFUL or HELPFUL in learning evolutionary concepts. For example, with respect to helping you understand evolutionary concepts, if you found "The readings" more useful or helpful compared to "Creating the lesson plan", then you would place a check mark in the box under "The readings".

Example: The readings vs. Creating the lesson plan

NOTE: Please CIRCLE all those resources that you did NOT use. For example, if you created a lesson plan but did not use all the readings then you would do the following:

For each pair listed, place a check mark in the box under the resource that you found MOST USEFUL or HELPFUL in learning evolutionary concepts. Circle all those resources that you did not use.

<table>
<thead>
<tr>
<th>Resource Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>The readings vs. The Web Resource</td>
</tr>
<tr>
<td>The readings vs. Doing the computer simulation</td>
</tr>
<tr>
<td>Personal knowledge/university vs. Completing questionnaires</td>
</tr>
<tr>
<td>The Web Resource vs. Doing the concept map</td>
</tr>
<tr>
<td>The readings vs. Doing the concept map</td>
</tr>
<tr>
<td>The Web Resource vs. Personal knowledge/university</td>
</tr>
<tr>
<td>The Web Resource vs. Discussions in my group</td>
</tr>
<tr>
<td>Discussions in my group vs. Doing the computer simulation</td>
</tr>
<tr>
<td>Completing questionnaires vs. Discussions in my group</td>
</tr>
<tr>
<td>The Web Resource vs. Doing the lesson plan</td>
</tr>
<tr>
<td>The Web Resource vs. Completing questionnaires</td>
</tr>
<tr>
<td>Completing questionnaires vs. The readings</td>
</tr>
<tr>
<td>Doing the lesson plan vs. Personal knowledge/university</td>
</tr>
<tr>
<td>Doing the computer simulation vs. The Web Resource</td>
</tr>
<tr>
<td>Resource Pairs</td>
</tr>
<tr>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Completing questionnaires vs. Doing the computer simulation</td>
</tr>
<tr>
<td>Doing the concept map vs. Personal knowledge/university</td>
</tr>
<tr>
<td>Discussions in my group vs. Doing the concept map</td>
</tr>
<tr>
<td>Doing the computer simulation vs. Doing the lesson plan</td>
</tr>
<tr>
<td>Doing the lesson plan vs. The readings</td>
</tr>
<tr>
<td>Personal knowledge/university vs. Doing the computer simulation</td>
</tr>
<tr>
<td>The readings vs. Discussions in my group</td>
</tr>
<tr>
<td>Doing the lesson plan vs. Completing questionnaires</td>
</tr>
<tr>
<td>Doing the computer simulation vs. Doing the concept map</td>
</tr>
<tr>
<td>Discussions in my group vs. Doing the lesson plan</td>
</tr>
<tr>
<td>Personal knowledge/university vs. Discussions in my group</td>
</tr>
<tr>
<td>Doing the concept map vs. Doing the lesson plan</td>
</tr>
<tr>
<td>The readings vs. Personal knowledge/university</td>
</tr>
<tr>
<td>Doing the concept map vs. Completing questionnaires</td>
</tr>
</tbody>
</table>

2) Compared with the average person, my computer skill/literacy is:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Well below</td>
<td>A little below</td>
<td>Average</td>
<td>Slightly above</td>
<td>Well above</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>average</td>
<td>average</td>
<td>average</td>
<td>average</td>
</tr>
</tbody>
</table>
Appendix E

MicroAnts Simulation: Manual

Instruction Manual for Running and Analyzing the MicroAnts Simulation
Instruction Manual for Running and Analyzing the MicroAnts Simulation

INTRODUCTION
This is a computer simulation designed to model some common processes that occur when organisms inhabit an ecosystem. What you are going to do is create a computer environment that contains two different populations of virtual ants; a population of red ants and a population of black ants. Once you have created the virtual ecosystem and it has been populated with red and black ants, you are going to run the simulation and then periodically record how the populations of ants are doing as they interact in their virtual world.

GOAL
Your group has ONE goal to accomplish:

To help you with this goal, after you have run the simulation, you will be asked to answer 4 or 5 questions related to the ant populations. You will need to refer to graphs of population statistics to help you answer these questions. The data for these graphs are saved by you as you progress through the simulation. The graphs of the population data will be produced after you have finished running the simulation.

THE GENE SCHEME (Please refer to the "Gene Scheme" at the end of this manual)
Every ant that lives in the ecosystem has 9 characteristics or traits. These characteristics are a result of 9 "genes" that can vary from ant to ant. You can think of these 9 genes as an ant's chromosome. These genes affect how the ant behaves and interacts in the virtual ecosystem.

When you setup the ecosystem, the computer will randomly generate the two populations of ants. When you run the simulation, the ants will begin to interact with their environment and each other. These interactions will affect the characteristics of the populations as the simulation progresses. Please keep the "gene scheme" handy because it could be useful when you begin to think about the goal noted above.

Important: You'll notice the simulation interface is fairly simple compared to most of today's windows programs. You must take care to key in numbers and values correctly before pressing <enter>. If you happen to process a mistyped value, you may have to start the simulation over.

START the simulation by typing "ants" at the DOS prompt and press enter.

(Please turn to the "Setting Up" section in the manual.)
Press a key and you will see the MicroAnts Environment Setup screen. Use the parameters below to setup your ecosystem. *Be sure to type the numbers carefully.* After you've keyed in a parameter, press <enter>.

- Number of Red Ants → 100
- Number of Black Ants → 100
- Initial Number of Food → 500
- Number of Food Grown in One Year (999 for 1 eaten, 1 grown) → 10
- Maximum Number of Food → 1000
- Number of Poison → 5
- Average number of crossovers per 1 hundred matings (0..100) → 25
- Average number of inversions per 1 hundred matings (0..100) → 5
- Average number of mutations per 1 hundred bits (0..100) → 4
- Minimum difference between combat points for one ant to kill another ant. (10000 for No Kills) → 100
- Speed of simulation: [F]ast or [S]low (press 'f' or 's' to choose) s
  
  *You don't have to press <enter> after pressing 's'. The next screen will appear automatically.*

Now you'll see the screen that allows you to set the environment's colours: Use the numbers indicated below. They tend to produce the best results.

- Background color (1..15) → 1
- Food color → 2
- Poison Color → 15

Next, you'll see the MicroAnts Main Menu.

(Please turn the page.)

**Notes:**

- a - The amount of food placed in the ecosystem at the start of the simulation. All food is placed randomly on the screen.
- b - The "growth rate" of the food. Thus, in the example above, only 10 new food items will appear in a "year".
- c - The total amount of food that the ecosystem can hold. Think of a farmer's field. It can only grow so many stalks of corn.
- d - The total amount of poison in the environment. This will remain constant, even if an ant eats it.
- e - The probability of a "crossover" for each 100 matings. Ant crossovers are similar in concept to genetic crossovers in us.
- f - The probability of an "inversion" for each 100 matings. Ant inversions are similar in concept to genetic inversions in us.
- g - The probability of a "mutation" for each 100 matings. Ant mutations are similar in concept to genetic mutations in us.
- h - See the "gene scheme" (genes 8 & 9) for an explanation of how this parameter affects whether an ant is killed.

An ant "year" is considered one cycle of all events that occur to all ants in the ecosystem at a given time. So, if there are 200 ants in the population, the next "year" begins after all 200 ants have performed their individual actions.
SAVING & EXAMINING

Before running the simulation you must do 2 things:

1) Save the baseline population data so that it can be analyzed later.

2) Examine the two population of ants and their environment.

!! SAVE !

 Saving data is an important aspect of the simulation and it's really easy to do.

 From the Main Menu: Press 'c' (Save Ant Statistics).
 Because this is "time 0" (baseline) data, save the file as: "time0.txt". You will be required to save data in this way at least 6 others times during the simulation.

EXAMINE

 From the Main Menu: Press 'e' (View Ant Statistics)
 You'll see nine columns of data. The '#' column provides a total count of the number of ants alive in the population. The 'ID#' is a unique identification number that is attached to an ant from the time it is born until it dies. The food, age, color, and chromosome columns will give you some idea of what the individual ants are like in each of the two populations. Don't worry about the exact meaning of the Gen, Parent 1, and Parent 2 column.

It is these population data that you will be saving and analyzing in your attempt to achieve your goal:

 From the Main Menu: Press 'g' (View Universe Statistics)
 Examine the statistics for the "universe". The most important number on the screen is the first one, the "Year:". This is a rough indicator of how many "generations" have passed since you started the simulation.

NOTE: Each time you pause the simulation and save the population data, you should take some time to examine the "ant statistics" to see how the ants are doing. For example, in addition to pressing 'e' or 'g' at the main menu, after you've run the simulation for a while, press 'f' (View Best Ant Hall of Fame) at the main menu. The statistics presented in this summary will provide details on the "top 10" performers in the population. This exploration may help you achieve your goal.

(Please turn to the "Running" section in the manual.)
RUNNING the SIMULATION

Now we are going to let "nature takes its course" by running the simulation. In order to see how the populations of ants are doing in this environment, you'll need to save the data about once every minute. Please designate a member of your group to keep track of the time. This length of time should give you a good snap shot of what is happening to the population of ants as they interact within the virtual ecosystem. At the END of "time4" you are going to change some environmental parameters and then continue running the simulation. Just as a reminder, your general goal is to:

! Check off each step as you do it! (Step 1 should already be done, so it has been checked for you.)

Steps

<table>
<thead>
<tr>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;Time0&quot; (Baseline)2</td>
</tr>
<tr>
<td>1) Press 'c' @ the MM and save Ant Statistics Use filename time0.txt</td>
</tr>
</tbody>
</table>

Before continuing, please discuss the following question

Question 1

Your computer has just randomly generated 200 virtual ants. Each of the other groups is using the same program and has entered the same environmental parameters. Will YOUR group's description of how the population of ants changes over time be similar or unique compared to other groups? Please explain the reasons for your answer.

When your group has answered this question, please go to step 2. Make sure your "timer" is ready!

2) Press 'a' @ the MM to run the simulation Run for about 1 min. or so then go to step 3

"Time1"

3) Press any key to pause the simulation.
4) Press 'c' @ the MM and save Ant Statistics. Save statistics using filename time1.txt Run for another 1 min. or so then go to step 6

"Time2"

6) Press any key to pause the simulation.
7) Press 'c' @ the MM and save Ant Statistics. Save statistics using filename time2.txt Run for another 1 min. or so then go to step 9

"Time3"

9) Press any key to pause the simulation.
10) Press 'c' @ the MM and save Ant Statistics. Save statistics using filename time3.txt Run for another 1 min. or so then go to step 12

"Time4"

12) Press any key to pause the simulation.
13) Press 'c' @ the MM and save Ant Statistics. Save statistics using filename time4.txt Run for another 1 min. or so then go to step 15

Please Turn the Page and Do Step 14

NOTES: * = Very important step! Be sure to use the correct naming style.
<table>
<thead>
<tr>
<th>Steps</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image_url" alt="Image" /></td>
<td><img src="image_url" alt="Image" /></td>
</tr>
</tbody>
</table>

14) Press '#1' @ the MM and **change Env. variables.** Enter NEW enviro variables below

- 15) Press 'a' @ the MM and continue to **run the sim.** Run for another 1 min. or so then go to step 16

**"Time5"**

- 16) Press any key to **pause the simulation.**
- * 17) Press 'c' @ the MM and **save Ant Statistics.** Save statistics using filename **time5.txt**
- 18) Press 'a' @ the MM and continue to **run the sim.** Run for another 1 min. or so then go to step 19

**"Time6"**

- 19) Press any key to **pause the simulation.**
- * 20) Press 'c' @ the MM and **save Ant Statistics.** Save statistics using filename **time6.txt**
- 21) Press 'a' @ the MM and continue to **run the sim.** Run for another 1 min. or so then go to step 22

**"Time7"**

- 22) Press any key to **pause the simulation.**
- * 23) Press 'c' @ the MM and **save Ant Statistics.** Save statistics using filename **time7.txt**
- 24) Press 'a' @ the MM and continue to **run the sim.** Run for another 1 min. or so then go to step 25

**"Time8"**

- 25) Press any key to **pause the simulation.**
- * 26) Press 'c' @ the MM and **save Ant Statistics.** Save statistics using filename **time8.txt**
- 27) Press 'a' @ the MM and continue to **run the sim.** Run for another 1 min. or so then go to step 28

**"Time9"**

- 28) Press any key to **pause the simulation.**
- * 29) Press 'c' @ the MM and **save Ant Statistics.** Save statistics using filename **time9.txt**

Please do not "Quit" the simulation. After you have completed step 29 please turn the page and begin the "Data Analysis".

Please turn the Page and continue with "Data Analysis"

**NOTES:**

* = Very important step! Be sure to use the correct naming style.
DATA ANALYSIS

To begin analyzing the simulation data, press and hold the "Alt" key and then press the "Tab" key and release it. The program EXCEL should appear, and the file for analyzing the data (ants.xls) should already be open.

You can begin processing the simulation data by going to the "Intro" worksheet and SINGLE click the red button labeled, "Process The Data Files". There is a lot of data produced in the simulation so it will take some time to analyze it all. Please follow the screen instructions as they appear and if you have any questions, please ask.

All the graphs produced by this analysis can be found by clicking on the EXCEL worksheet labeled "Data Summary".

Once the simulation data have been processed, please turn the page and begin answering the questions provided.
Phase 2 (Familiarization): Questions for Group Discussion

Introduction
In your groups, please discuss answers to the questions listed below. It is important that you feel free to share your ideas on each question. Evolution can be a difficult and controversial subject for many and getting other people's perspectives on the subject can be helpful.

Each person in your group should try to help with the answer to a question. Only move on to the next question when all the members of your group are satisfied that a well-supported answer has been provided.

Technical Details
Make sure your microphone is on! When you are ready to begin, start the tape player and record your discussion. Please answer the following question before running the simulation.

1) Your computer has randomly generated 200 virtual ants. Each of the other groups is using the same program and has entered the same environmental parameters. In terms of describing how the population of ants changes, will YOUR group's description of how the population of ants has changed over time be similar or unique compared to the other groups in the study? Please explain.

PLEASE ANSWER QUESTION 2 AFTER YOU HAVE CHANGED THE ENVIRONMENTAL VARIABLES IN STEP 19.

2) You have just changed some of the environmental parameters in the virtual ecosystem. Given what you know already from examining some of the population statistics for the existing ants, in what way(s) (please be specific!) do you think these changes will affect the population of ants over the remaining five time periods?

Answer question 3 after data have been processed with the EXCEL program.

3) Use any of the gene graphs 3-11 to answer the following question. Look at the proportions of red and black ants that are ALIVE for 2 or 3 different gene graphs at "TIME 0" only. For "time 0", explain why the proportions of ants (red or black) for any given graph are roughly equal in value.

If you have an answer, please explain why you think this is important for the ways in which the ant population changes over time.

4) Look at the numbers of red and black ants in the population that remained alive between "time 0" and "time 1" (see Graph # 1). What is the most likely explanation for why such a change (if any) occurred between "time 0" and "time 1"?

5) Are the ants able to change important characteristics related to their survival? In other words, what is the distinction between saying an ant can adapt (using adapt as a verb) to its environment versus saying an ant has adaptations (using adapt as a noun) for its environment?

6) Is evolution a phenomena that happens to individuals or to populations? Please explain the reasons for your answer. Feel free to make reference to the graphs on the "Data Summary" spreadsheet to support the reasons for your answer.

7) Is selection a phenomena that happens to genes, to individuals, to populations or to species? Please explain the reasons for your answer. Feel free to make reference to the graphs on the "Data Summary" spreadsheet to support the reasons for your answer.

8) In the context of the simulation, did anything resembling evolution by natural selection actually occur? Please explain the reasons for your answer. Feel free to make reference to the graphs on the "Data Summary" spreadsheet to support the reasons for your answer.
Phase 4 (Exploration): Questions for Group Discussion

There are 5 questions to answer (questions 2 - 6). Please try to provide an answer for all 5 questions in the time you have remaining.

**EACH PERSON IN YOUR GROUP SHOULD TRY TO HELP WITH THE ANSWER TO A QUESTION.**

**ONLY MOVE ON TO THE NEXT QUESTION WHEN ALL THE MEMBERS OF YOUR GROUP ARE SATISFIED THAT A WELL-SUPPORTED ANSWER HAS BEEN PROVIDED.**

**Question 2 - Part 'A' & Part 'B'**

**NOTE: TIME 0 = What the population of red and black ants are like BEFORE the simulation began.**

**Part 'A'**
Use the "Moving Genes" graph (#4) to help you answer the following question:

**LOOKING AT TIME 0 ONLY, examine the percentage of red and black ants that have a particular expression of this gene.** As you can see from the Moving Genes graph, both red and black ants can have 1 of 4 types (expressions) of moving genes:

1) "None" (The ant does not move unless it sees food, then it moves to consume it)
2) "U/D" (The ant moves up and down unless it sees food, then it moves to eat it and then continues moving U/D)
3) "L/R" (The ant moves left and right unless it sees food, then it moves to eat it and then continues moving L/R)
4) "Random" (The ant moves randomly unless it sees food, then it moves to eat it and then continues moving U/D)

**FOR TIME 0 ONLY, explain why you think the percentage of ANY of these 4 types of moving genes in the population (red or black ants) is roughly equal.** You may want to look at 1 or 2 other graphs to confirm the pattern that AT TIME 0 ONLY, the percentage of ants that are expressing different types of that gene are roughly equal. You need to explain why this pattern exists.

**Part 'B'**
Do you think your answer for part 'A' above has any influence on what happens to the ants as they interact in this ecosystem? Please explain your answer.

**Question 3**
This question refers to the "Poison-avoidance Genes" graphs (# 5, alive or dead graphs). Do you think that these graphs indicate that there is a need among the red and black ants to avoid poison? Please explain your answer.

Please turn the page and continue with Question #4
**Question 4**
When answering this question please choose **ONE** (1) of the gene graphs and make reference to it in explaining your answer.

What is the difference between saying an ant is adapting (using "adapt" as a verb) to its environment versus saying an ant has an adaptation (using "adapt" as a noun) for its environment? Remember, please make reference to only **ONE** (1) of the gene graphs for your answer.

**Question 5**
When answering this question please try to refer to one or two of the gene graphs.

In this simulation, do you think anything resembling "evolution by natural selection" occurred with the population of red and black ants? Please explain the reasons for your answer.

**Question 6 - Parts 'A' & 'B'**

**Part 'A'**
When answering this question please try to refer to **one or two** of the gene graphs.

What does "survival of the fittest" mean? Please explain your answer.

**Part 'B'**
When answering this question please try to refer to **one or two** of the gene graphs.

Could an ant be weak (strength = 1), cowardly (attacks = 0 - never) and lazy (movement = 0) and still be fit? Please explain your answer.

**EXTRA QUESTION (if you have time)**
This question pertains to the "Poison-avoidance Genes" graph (#5) for **DEAD** ants (the **blue** button of graph #5).

**Part 'A'**
Please provide a general interpretation of this graph at **TIME 1 ONLY**. That is, describe in words what you think the graph is telling you at **TIME 1**.

**Part 'B'**
Are there any general **conclusions or implications** regarding the information contained in this graph? Please explain your answer.
The MicroAnts Gene Scheme: “Genes” 1, 2 (bits 1-6)

<table>
<thead>
<tr>
<th>BITS &gt;&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16</td>
</tr>
<tr>
<td>i i i i 2 2 3 4 5 5 6 7 8 8 9 9</td>
</tr>
</tbody>
</table>

GENES >>

Gene # 1 (Bits 1 – 4): Ant's vision for food (Range: 0 – 15)

<table>
<thead>
<tr>
<th>Ants vision for food (Range 0-15 squares)</th>
<th>The code to enter for gene # 1 when creating your own Ant (Bits 1-4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – Ant is blind</td>
<td>0000</td>
</tr>
<tr>
<td>1 – Ant can see food 1 square away</td>
<td>0001</td>
</tr>
<tr>
<td>2 – Ant can see food 2 squares away</td>
<td>0010</td>
</tr>
<tr>
<td>3 – Ant can see food 3 squares away</td>
<td>0011</td>
</tr>
<tr>
<td>4 – Ant can see food 4 squares away</td>
<td>0100</td>
</tr>
<tr>
<td>5 – Ant can see food 5 squares away</td>
<td>0101</td>
</tr>
<tr>
<td>6 – Ant can see food 6 squares away</td>
<td>0110</td>
</tr>
<tr>
<td>7 – Ant can see food 7 squares away</td>
<td>0111</td>
</tr>
<tr>
<td>8 – Ant can see food 8 squares away</td>
<td>1000</td>
</tr>
<tr>
<td>9 – Ant can see food 9 squares away</td>
<td>1001</td>
</tr>
<tr>
<td>10 – Ant can see food 10 squares away</td>
<td>1010</td>
</tr>
<tr>
<td>11 – Ant can see food 11 squares away</td>
<td>1011</td>
</tr>
<tr>
<td>12 – Ant can see food 12 squares away</td>
<td>1100</td>
</tr>
<tr>
<td>13 – Ant can see food 13 squares away</td>
<td>1101</td>
</tr>
<tr>
<td>14 – Ant can see food 14 squares away</td>
<td>1110</td>
</tr>
<tr>
<td>15 – Ant can see food 15 squares away</td>
<td>1111</td>
</tr>
</tbody>
</table>

An ant possessing sight can see food in all 4 directions: up, right, left, and down. If an ant moves onto a food spot, then the ant adds 10 to its food level. Otherwise, it an ant moves and doesn’t find food it loses 1 food level. An ant can’t store more than 9,999 food points. An ant dies when its food level reaches 0.

An ant which can see food and can detect poison will move toward the food closest to the ant. If there is poison between an ant and food, the ant will not be able to see the food (only the poison, which it will avoid).

Gene # 2 (Bits 5 – 6): How the Ant Moves (Range: 0 – 3)

<table>
<thead>
<tr>
<th>How an Ant moves (Range 0 - 3)</th>
<th>The code to enter for gene # 2 for creating your own Ant (Bits 5-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – The ant doesn’t move unless it sees food</td>
<td>00</td>
</tr>
<tr>
<td>(then it moves to consume it and continues U/D movement)</td>
<td></td>
</tr>
<tr>
<td>1 – The ant moves up and down unless it sees food</td>
<td>01</td>
</tr>
<tr>
<td>(then it moves to consume it and continues L/R movement)</td>
<td></td>
</tr>
<tr>
<td>2 – The ant moves left and right unless it sees food</td>
<td>10</td>
</tr>
<tr>
<td>(then it moves to consume it and continues random movement)</td>
<td></td>
</tr>
<tr>
<td>3 – The ant moves in a random direction unless it sees food</td>
<td>11</td>
</tr>
<tr>
<td>(then it moves to consume it and continues random movement)</td>
<td></td>
</tr>
</tbody>
</table>

Movement (Gene # 2, bits 5-6)

If an ant can move, it can move in 4 directions: up, right, left, and down. If the ant's chromosome dictates that the ant will move up and down, and if it can detect poison; then if it encounters poison, it will begin moving right and left.

If an ant with BITS 5 and 6 of 01 or 10 can't move up, it will first try to move right. If it can't move right, it will try to move down. If it can't move down, it will try to move left. If it can't move left, it will try to move up.

If the ant will not move, but it can see poison and/or food, it will move toward the poison and/or food (depending on whether it can detect poison). If the ant will not move, and is either blind or can not see any food and/or poison, it will remain where it is.
Gene # 3 (Bit 7): Does the ant avoid poison/toxic food? (Range: 0 – 1)

Does an ant avoid Poison? (Range 0-1)  

0 – The ant does not avoid poison/toxic food  
1 – The ant avoids poison/toxic food

Poison (Gene # 3, bit 7)

An ant which cannot detect poison can not differentiate between food and poison. Thus, if it can see poison, it will go to it.

An ant which is completely surrounded by poison will kill itself by eating the poison (if it can move). It would rather die of poisoning rather than starvation. The chances of this happening are very small unless you put a whole lot of poison (>2000) in the environment.

Gene # 4 (Bit 8): Does the ant mate? (Range: 0 – 1)

Ant mating ability

0 – The ant mates if its food level > 500 points
1 – The ant mates if its food level > 1000 points

Mating may occur when two ants occupy the same spot in the environment. The number of matings depends on luck (two ants land on the same spot at the same time and have enough energy for the process) and genetics (some ants have higher energy requirements for mating than others). Mating reduces each ant’s food level by 500. Each baby ant starts out with a food level of 50. The baby ant is randomly placed on the screen (by the stork).

If both ants’ 8th bit is 0, then they will mate if both their food levels exceed 500. However, if at least 1 of the ants has an 8th bit of 1, then they will mate only if both their food levels exceed 1000. Thus, the ant with an 8th bit of 1 has influence over an ant with an 8th bit of 0.

EXAMPLE (Genes 1 - 4):

Ant sees 6 squares away.

Ant moves L & R

Ant avoids poison

Ant mates if food > 1000

01101011
The MicroAnts Gene Scheme: “Genes” 5-7 (bits 9-12)

BITS >>

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

GENES >>

Gene # 5 (Bits 9 – 10): Does the ant share its food? (Range: 0 – 3)

When ants share food (Range 0-3)

<p>| | | | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

The code to enter for gene # 5 when creating your own Ant (Bits 9-10)

- The ant never shares its food: 00
- The ant always shares its food: 01
- An ant with gene # 5 bits set to "10" shares its food with other ants having Gene # 5 bits set to "10": 10
- An ant with gene # 5 bits set to "11" shares its food with other ants having gene # 5 bits set to either "00" or "11": 11

Sharing (Gene # 5, bits 9-10)

An ant may share with another ant if an ant moves onto a spot occupied by another ant, and if the ant occupying that spot has a food level less than the food level of the ant moving onto that spot. Thus, the ant moving onto the spot decides whether or not to share food.

Gene # 6 (Bit 11): Can the ant see other ants? (Range: 0 – 1)

Can an ant see other ants? (Range 0-1)

<p>| | | | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

The code to enter for gene # 6 when creating your own Ant (Bits 11)

- The ant cannot see other ants: 0
- The ant can see other ants: 1

Seeing Other Ants (Gene # 6, bit 11)

If an ant can see food and other ants and if another ant is between itself and food, the ant will not go for that food (the other ant would get there first).

Gene # 7 (Bit 12): Can the ant see the anteater? (Range: 0 – 1)

Can an ant see the Anteater? (Range 0-1)

<p>| | | | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

The code to enter for gene # 7 when creating your own Ant (Bit 12)

- The ant cannot see the anteater: 0
- The ant can see the anteater: 1

Anteater (Gene # 7, bit 12)

An anteater (large gray spot) may sometimes move across the screen. If an ant cannot see it, it may be eaten by it, in which case EATINGS in VIEW UNIVERSE STATISTICS increases by one.
The MicroAnts Gene Scheme: “Genes” 8-9 (bits 13-16)

BITS >>

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
| GENES >>

Gene # 8 (Bit 13 - 14): Does the ant attack other ants?? (Range: 0 – 3)

Does an ant attack other ants? (Range 0-3) The code to enter for gene # 8 when creating your own Ant (Bits 13-14)

<p>| | | | | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Attacking/Fighting (Gene # 8, bits 13-14) & Strength (Gene # 9, bits 15-16)

When one ant (Ant A) lands on another ant (Ant B), gene 8 of ant A determines whether or not it attacks ant B. If there is an attack, the ant with the most combat points wins. However, the winning ant will not kill the losing ant if the difference in their combat points does not exceed the "Minimum-Difference-between-combat-points-for-one-ant-to-kill-another-ant" parameter you enter when setting up the ecosystem. So, if combat does occur (gene # 8 determines this), then the following algorithm decides the winner (if there is one).

\[
\text{Ant A's combat points} = \text{strength} \times (\text{random(previous kills)} + \text{food_level}/10)
\]
\[
\text{Ant B's combat points} = \text{strength} \times (\text{random(previous kills)} + \text{food_level}/10)
\]

If Ant A's combat points > Ant B's combat points + "Minimum Difference parameter" then Ant 1 kills Ant 2 and Ant 1 gets Ant 2's food.
If Ant B's combat points > Ant A's combat points + "Minimum Difference parameter" then Ant 2 kills Ant 1 and Ant 2 gets Ant 1's food.

Note: The "random(previous kills)" in the formula above means a random value between 0 and the number of previous kills for that ant. Thus, successful combat experience improves an ant's ability to fight. However, the random factor means an inexperienced ant can beat an experienced fighter through luck.

Gene # 9 (Bit 15 - 16): How much strength does the ant have? (Range: 1 – 4)

An ant's strength (Range 1-4) The code to enter for gene # 9 when creating your own Ant (Bits 15-16)

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

EXAMPLE (Genes 5 - 9):

Ant always shares its food.
Ant can't see other ants
Ant sees anteater
Ant attacks only red ants
Ant's strength is 3
Appendix F

Letter of Informed Consent

Dear Student,

This letter invites you to participate in a research project/professional development workshop designed to investigate how a computer simulation of biological processes affects conceptual understanding of these processes. The study is being conducted by Ron Macdonald and Dr. Erminia Pedretti of the Department of Curriculum, Teaching and Learning at OISE/UT. The main purposes of the project are: 1) to examine how a simple computer-simulated ecosystem, visual representations of the simulation data, and small-group discussion can affect conceptual understanding of the biological processes operating in the ecosystem, 2) to illuminate the strengths and weakness pre-service science teachers may have regarding their conceptions of these processes, 3) to strengthen pre-service science teachers' understanding of the nature of science as it relates to the use of theories and the use of data as evidence in support (or refutation) of theories and, 4) to suggest ways that computers can be integrated as a learning tool in a science curriculum.

Your participation in the project will require a total of about six hours of your time over the course of the first term. If you agree to participate in this project you will receive the following: 1) a copy of the simulation software, 2) a copy of the data analysis program and all related manuals for both programs, 3) a compilation of resource materials (lesson plans, concept maps, web-site resources) produced by project participants, and 4) a stipend of $50.00, payable upon completion of the project.

In the course of the first term, you will be asked to complete three surveys (some class time will be allotted for this). The first survey asks questions related to your attitudes and ideas towards the nature of science. The second survey examines your attitudes toward teaching biological concepts with your students. The third survey asks questions related to your background in biology and your understanding of biological concepts.

Also, we will meet in one of the computer labs at OISE/UT to become familiar with the computer-simulated ecosystem. We will work in small groups to explore and to discuss the simulation and utilize related web-based resources. From this resource (or any other curriculum resources to which you have access), your group will develop a lesson plan on natural selection that would be suitable for a one-hour lesson in a grade 12 or grade 13 biology class. We will meet in the computer lab on another occasion to explore the simulation in more detail.

Finally, we will meet for one hour for the purpose of developing individual concept maps of the material you've investigated in the previous sessions. After the concept maps have been completed a general discussion about the project will take place in the remainder of the hour. Some of our discussions will be audio-taped.

Any information obtained during this project will be treated confidentially. Your name will not be used in any publications or reports related to this research. All information will be kept in locked cabinets and only the principal investigators will have access to these files. You participation or refusal to participate in this research will have no affect on the grade you receive in any course.

If you have any questions about this research, please feel free to contact me, Ron Macdonald, at the following email address: rmacdonald@oise.utoronto.ca. I can also be reached during the day on the 11th floor at OISE/UT, office 267.

--------------------------------------------------------------------------------------------------
Letter of Information: Informed Consent

☐ I agree to participate and grant permission to allow my discussions related to this project to be audio-taped.

☐ I understand that I am free to withdraw from the study at any time and for any reason. I understand that if I choose to discontinue my participation in the study, this decision will in no way affect the grades I receive in any course I take.

☐ I understand that there is unlikely to be any foreseeable harm or negative consequence as a result of my participation in this investigation.

☐ I understand the purpose of this research, as outlined in the letter of information, regarding the research project on how a computer simulation of biological processes affect conceptual understanding of these processes.

☐ I do not wish to participate in this study.

Print name: ____________________________

Signature: ____________________________ Date: ____________________________

*Email address: ____________________________ *Phone #: ____________________________

• Your email address and telephone number will only be used for the purposes of arranging meetings and informing you if a change in scheduling has occurred.
Appendix G

Debriefing Information

Dear Participant,

Thank you for your help with this project. I am hopeful you found it a valuable, entertaining and educational experience. Increasingly, computer simulations have become important pedagogical tools for illustrating complex phenomena (Thompson & Hooper, 1991). The MicroAnts simulation was used because it was simple, focused on relevant concepts, allowed users to explore a process that cannot easily be observed in nature, and produced data that could be easily represented for analysis.

You were placed into small groups based on the score you received on the evolution knowledge survey. This survey was designed to examine your understanding of basic evolutionary concepts (Jensen & Finley, 1996). In most instances, individuals who scored low on the survey were paired with individuals who scored intermediate or high. The rationale for these groupings was based on the sociomoral literature that has shown improvements in reasoning about moral issues among dyads who were moderately disparate in levels of moral reasoning (Berkowitz & Gibbs, 1985). It was expected that this same effect might occur in reasoning about a scientific phenomena. The discussions were recorded so that they could be analyzed for the kinds of reasoning the dyads and triads used in answering questions related to the simulation.

The survey that asked questions about your personal views on teaching evolution was designed to examine factors that might influence your intentions to teach evolutionary theory with your students (Ajzen, 1985).

The survey that asked for your views on the nature of science (Part A, B) was designed to examine how you view the domain and practice of science. Several different dimensions of science epistemology were inherent in these surveys (Aikenhead & Ryan, 1992; Nott & Wellington, 1993). Evolutionary knowledge, intentions to teach evolution and views on the nature of science will be examined for interrelationships.

The Web-site was created to provide you with information and resources related to evolutionary theory. This computer based compilation was designed to be easily accessible, entertaining, and informative.

The concept maps were used as a means of examining if any conceptual change had occurred over the course of the investigation.

Together, each individual's results from the surveys, their small-group discussions, the lesson plans, and concept map will be used to get an overall picture of the conceptions pre-service science teacher have about evolutionary theory and how those conceptions might influence their teaching practice.

If you have any questions about this research, please feel free to contact me, Ron Macdonald, at the following email address: rmacdonald@oise.utoronto.ca. I can also be reached during the day on the 11th at OISE/UT, office 267.

References


Appendix H

INITIALS: ___________ Evolution By Natural Selection: Concept Map

Instructions
On the second page of this handout you will find a sheet of paper with five "seed" concepts listed across the top. After reading the instructions below, please create a concept map that details your understanding of evolution by natural selection. Note that there is no single "best" way to complete a concept map. What is important is how you view the nature of the relationships among concepts.

Remember:
1) You must use all five "seed" concepts in your concept map. Feel free to arrange the seed concepts in any way you would like.

2) You should try to create your concept map in such a way so that it includes at least four new concepts (see example below).

3) You should relate the arrangement of your concepts with "linking" words and phrases. These linking words and phrases should convey the essential nature of the relationship among concepts. Thus, your linking words or phrases can be nouns, verbs, adjectives, adverbs, conditional clause (e.g., if ... then ...), or any combination of these as long as you clearly establish how the concepts are related. Please be as specific as possible when linking concepts.

4) If you use arrows (you do not need to), then the use of a one-way arrow (→) between concepts indicates that one concept causes or brings about change in the other. If you use a two-way arrow (↔), then this indicates that each concept effects some degree of change in the other.

Example
To give you some idea of what is expected, here is an example of a concept map about driving.

Seed Concepts: Engine Gasoline Driver The Road

Driver
          purchases
          controls
          Demands attention
          To run properly
          must have
          Is used by
          must have
          may require

Gasoline

Engine

The Road

Consumption will lead to depletion of

Gray Ellipses =
Evolution by Natural Selection

Seed Concepts: (no particular order)

- Genes
- Population
- Environment
- Mutations
- Natural Selection
Appendix I

Final Interview

Content Questions

1) Cheetahs, (large African cats) are able to run faster that 100 km/hr when chasing prey. How would a biologist explain how the ability to run fast evolved in cheetahs, assuming their ancestors could only run 40 km/hr?

2) Cave salamanders are blind (they have eyes which are not functional). How would a biologist explain how blind cave salamanders evolved from sighted ancestors?

Simulation Questions

3) What did you think of the simulation?

4) In what ways was the simulation useful or helpful to you in understanding evolutionary concepts?

5) In what ways was the simulation confusing or not helpful to you in understanding evolutionary concepts?

6) Any comments or questions about the study?