DESIGN AND IMPLEMENTATION OF COMPUTER-BASED SCAFFOLDING FOR IMPROVING PROBLEM SOLVING IN UNDERGRADUATE SCIENCE

by

HYUN SONG KIM

(Under the Direction of Janette R. Hill and J. Michael Spector)

ABSTRACT

Many college students have difficulties in employing an appropriate problem-solving process to attempt solutions for science problems. Therefore, instructional support or guidance is necessary to develop students' problem-solving ability. This dissertation focuses on the advancement of theory and practice in computer-based scaffolding to enhance college students' problem-solving skills in science education contexts.

This dissertation consists of three journal-ready manuscripts that together are designed to provide additional insights into the use of computer-based scaffolding in science education. The first manuscript provides an overview of a potential scaffolding design framework. Grounded in the scaffolding framework, a self-directed, online tutorial program, *SOLVEIT*, was designed to support the development of college students' problem-solving skills within the domain of biology. *SOLVEIT* guides students through the entire process of solving a science problem with the assistance of various scaffolds (e.g., prompts, interactive tutorials, and expert models): clarifying the problem, analyzing scientific data, examining possible assumptions and drawing a conclusion. The second and third manuscripts were intended to examine the effectiveness of *SOLVEIT* and provide some of the missing empirical evidence to support the design of effective computer-based scaffolding for science problem solving. The collected data suggest that *SOLVEIT* is a promising tutorial program to better customize the instructional experience of students in an introductory science course. The results from the data collection and analysis led to the design of a refined scaffolding framework and suggestions to advance *SOLVEIT* for broader usage.

INDEX WORDS: Biology, Educational design research, Scaffolding, Scaffolds, Online tutorial program, Post-secondary science education, Problem-solving skills, Undergraduate students

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DEDICATION

This dissertation is dedicated to my dear husband as well as my best friend, Kyung-Jin. This work is also dedicated to my parents, Jeong-Ryong Kim and Guem-Soon Shin, and my younger sister, Haesong Kim. Thank you for your love and support during this journey.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

One of the crucial goals of a college of education is preparing scientifically literate citizens who can resolve complex problems in the real world (National Research Council [NRC], 2012). Scientifically literate adults should be able to identify and interpret problems, plan and implement feasible problem-solving processes, monitor those processes, and generate and evaluate possible solutions (Jonassen, 2011). For the past few decades, research has been carried out to understand human problem solving with different types of problems (e.g., well- and ill-structured problems in disciplines, such as computational reasoning, engineering design, environmental planning, technology integration, and physics, see Spector, 2006), to generate problem-solving models (Bransford & Stein, 1993) and to explain the differences between expert and novice problem solving (Chi, Feltovich, & Glasner, 1981). This body of research reveals the importance of developing students' problem-solving skills in formal educational contexts, and has led educational researchers to attempt to design and implement instructional models and strategies to improve and enhance students' problem-solving skills (Hsu & Heller, 2009; Jonassen, 2011; NRC, 2012).

Despite these efforts, students' deficiencies in problem solving remain a widely recognized problem, particularly in science education (Handelsman et al., 2004; Sandoval & Morrison, 2003). Devising learning activities that provide students with opportunities for practicing problem solving in science courses is important (American Association for the Advancement of Science [AAAS], 2011; Hoskinson, Caballero, & Knight, 2013). For example, some college science courses include laboratory writing (Quitadamo & Kurtz, 2007), invention activities (Taylor, Smith, van Stolk, & Spiegelman, 2010, in biology), or argumentation activities (Wisehart & Mandell, 2008) that allow students to engage in the scientific process through building hypotheses, analyzing data sets, and evaluating alternative solutions.

While solving problems in what may be considered experiential learning activities, many students need assistance from teachers. Instructional support, known as *scaffolding* (Palincsar & Brown, 1984), helps students attain a learning goal that would otherwise be beyond their abilities (Reiser, 2004). The concept of scaffolding has been used with the notion of the zone of proximal development, which refers to the difference between the actual level of independent problem-solving skills and the level of assisted problem-solving skills achieved with the support of an expert or more capable peers support (Vygotsky, 1978). According to Vygotsky's theory, students can complete a challenging task in the zone of proximal development with a teacher's support. As students become able to complete the task independently without assistance, scaffolding eventually fades away.

Unfortunately, due to a number of barriers, including limited classroom time, inadequate resources, and a lack of human resources, it is difficult for college instructors to provide the right amount of support and the right type of guidance to students, who usually present a wide range of needs and difficulties. Computer-based (i.e., automated) scaffolding may help teachers overcome this challenge. Recently, research has shown some evidence that computer-based scaffolding can be used effectively in science education to improve college students' problem-solving skills. For example, college students demonstrated improved conceptual understanding about molecular symmetry after using an online tutorial that provided visual representations of various molecular structures and allowed students to manipulate those representations (Korkmaz

& Harwood, 2004). According to Lin and Lehman (1999), metacognitive prompts in a computer-based simulation program help students learn how to control variables in biology experiments. However, despite agreement on the potential of computer-based scaffolding to improve students' problem-solving skills in college science education contexts, empirical research on how to design effective computer-based scaffolding is relatively sparse and not well elaborated. Moreover, only a few research studies conducted in K-12 contexts offer conclusive evidence for the effectiveness of computer-based scaffolds (c.f., Belland, 2010). Therefore, more empirical research is required to develop a sustainable computer-based scaffolding model for college science education.

Purpose of the Study

The purpose of this series of studies was to advance theory and practice in computer-based scaffolding in a science education context. The goals for this research were: (a) to create effective computer-based scaffolding that promotes the development of college students' knowledge and skills in solving complex science problems and (b) to generate a robust scaffolding design framework for supporting college students' problem solving in science. To attain these goals and guide the design process, educational design research was employed as a research framework (see Figure 1.1). Educational design research typically involves iterative cycles of design and development with data collection and analysis pertaining to the use and impact of an instructional intervention (Design-Based Research Collective, 2003; McKenney & Reeves, 2013; van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). In this way, educational design research can provide more conclusive and sufficient empirical evidence that leads to the design of more effective interventions.

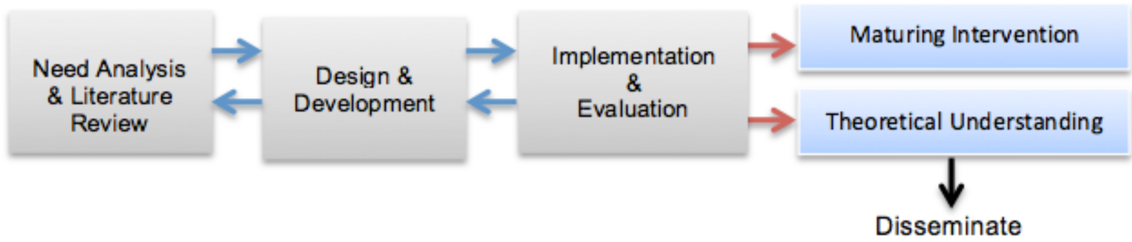

Figure 1.1. The educational design research process for this research (Adapted from McKenney & Reeves, 2013)

The studies described in this dissertation followed the building of a conceptual computer-based scaffolding framework based on a robust review of previous scaffolding literature (e.g., Hannafin, Land, Oliver, 1999; Hill & Hannafin, 2001; Reiser, 2004). Grounded in the scaffolding framework, a self-directed online tutorial program, *SOLVEIT*, was designed and developed through collaboration among researchers from several disciplines – instructional technology, biology education, and computer science. The current version of *SOLVEIT* provides students with problems in biological domains of evolution and ecology and takes them through the scientific problem-solving process with the assistance of various scaffolds (e.g., prompts, interactive tutorials, and expert models).

SOLVEIT was implemented in two phases (spring and fall 2012); various data were collected during the implementation to evaluate the effects of *SOLVEIT* on college students' problem-solving skills in an introductory biology course. The results from the data collection and analysis led to the design of a refined scaffolding framework and suggestions to advance *SOLVEIT* for broader usage in accordance with a design-based research framework.

Dissertation Chapter Overview

This dissertation consists of three journal-ready manuscripts that together are designed to provide additional insights into the use of computer-based scaffolding in science education. The first manuscript (Chapter Two) provides an overview of a potential scaffolding design framework; the second and third manuscripts (Chapters Three and Four) were intended to provide some of the missing empirical evidence to support the design of effective computer-based scaffolding for science problem solving.

Chapter Two

The first paper presents the theory-based conceptual framework underpinning this research. In this paper, we review and summarize the literature that has contributed to the design of scaffolding for science problem solving. We first discuss the characteristics of science problems and cognitive requirements for science problem solving. Then, we identify novice students' difficulties in solving science problems and review computer-based scaffolding to support their deficiencies. As a result of the review, guidelines and principles are suggested for researchers and practitioners to design computer-based scaffolding for science problem solving. The guidelines include the following: (a) help students have a concrete understanding of science concepts using conceptual scaffolds, (b) guide disciplined problem-solving processes using procedural scaffolds, (c) have students represent and articulate their problem space explicitly using representation scaffolds, and (d) encourage students to plan, monitor, and evaluate problem-solving processes using metacognitive scaffolds. In addition, problem-solving processes should be practiced in a context of actual problem solving. Lastly, the implications of these guidelines and future research are discussed. This manuscript will be submitted to the *Journal of Science Education and Technology*.

Chapter Three

Grounded in the suggested guidelines and principles from the conceptual framework described in Chapter Two, *SOLVEIT* was designed and developed. A usability study was conducted as the first design research iteration (Iteration One). The focus of this study was primarily to examine the experiences of the students with the scaffolding in *SOLVEIT* and the benefits to their problem-solving skills that they perceived. This study employed qualitative case study methodology. A small number of students were recruited from an introductory biology course at a large public university in the Southeastern United States in Spring 2012. The students expressed an overall positive perception of *SOLVEIT*. They reported that the explicit step-by-step and visual guidance helped them understand efficient problem solving processes, and that question prompts were helpful for correcting their misconceptions.

The participants also suggested some modifications to the *SOLVEIT* design. According to their comments, some redundant question prompts were eliminated, and unclear instructions were modified. A few minor system bugs were fixed. Another issue found was that some students overlooked some of the optional scaffolding in *SOLVEIT*. In turn, reminder messages were added to encourage students to use those optional features. Students reported that they were reluctant to use the writing feature of *SOLVEIT* (scaffolds for representation and articulation), but based on the data, the scaffolding appears to have helped students externalize and reflect on their thoughts. A message to emphasize the importance of representation may be added to motivate students to use the writing feature. Implications and limitations of this study are discussed. This manuscript was submitted to The *Journal of Computer Assisted Learning*.

Chapter Four

The third paper presents the second design research iteration (Iteration Two) and focuses on the impact of *SOLVEIT* on college students' problem-solving skills. A mixed-method study was conducted, including a quasi-experimental study and a qualitative case study, with a large number of participants in the same course in Fall 2012. A rubric and standardized test were used to measure students' problem-solving skills. The findings of this study also demonstrate the potential of computer-based scaffolding to improve students' problem-solving skills. Results indicated that students demonstrated enhanced conceptual understanding and reasoning from data.

The findings from this second iteration also suggest some changes for *SOLVEIT* and the scaffolding design framework. First, metacognitive scaffolding may be more effective when it is connected to students' domain-related incorrect answers; otherwise, many students do not pay much attention to metacognitive support. Second, the amount and types of scaffolding should be matched with the level of prior knowledge and skills of students. Third, as students develop their problem-solving skills over time, increasing students' autonomy in selecting scaffolding may be necessary to avoid cognitive load. In addition, *SOLVEIT* only included a limited number of problems and variety of content. The limited features will be refined in future studies. This manuscript will be submitted to *Science Education.*

Chapter Five

A final concluding chapter provides a synthesis of the three papers. It focuses on the key ideas and the new knowledge contributed by conceptual framework and research studies. Overall, the findings from this series of research studies indicate the ability of computer-based scaffolding to facilitate problem representation, conceptual understanding, and problem-solving processes in the context of science education. Chapter Five also describes the limitations of the studies and suggests how future research can and should be explored by researchers and instructional designers in science education or similar contexts.

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CHAPTER 2

LITERATURE REVIEW

COMPUTER-BASED SCAFFOLDING FRAMEWORK FOR COLLEGE SCIENCE PROBLEM SOLVING[1]

[1] Kim, H. S. & Spector, J. M. To be submitted to *Journal of Science Education and Technology*

Abstract

A crucial goal that cuts across disciplines in college science education is that of enhancing students' ability to solve complex science problems (National Research Council [NRC], 2012). The purpose of this paper is to provide a conceptual framework that guides future research regarding the design of computer-based scaffolding to support science problem solving. We reviewed and summarized findings from several different fields of research that have contributed to the design of scaffolding for problem solving: (a) characteristics of science problems, (b) the knowledge and skills required for science problem solving, (c) novice students' difficulties in solving science problems, and (d) roles of computer-based scaffolding to support novice students' science problem solving and its limitations. As a result of our review, we suggest guidelines for designing computer-based scaffolding for science problem solving and discuss the implications. Last, we make recommendations for future research.

Introduction

Problem solving is a central focus of college science education (Docktor & Mestre, 2011; National Research Council [NRC], 2012). Students should be able to develop a reasonable answer to or solution for a science problem through the application of appropriate principles, laws, and theories related to the problem (American Association for the Advancement of Science [AAAS], 2011; Bybee et al., 2006; NRC, 2003). However, in general, solving science problems is a demanding task for college students. Research studies in physics (Chi et al., 1981; Maloney, 1994), biology (Nehm & Ridgway, 2011), and chemistry (Sumfleth, 1988) have demonstrated that many students have limited knowledge and skills in solving science problems.

Computers have previously been shown to enrich science instruction. Moreover, the effectiveness of some computer-based scaffolding strategies for supporting scientific inquiry has been empirically validated, mostly in K-12 contexts (e.g., Songer, 2006). Scaffolds refer to instructional supports to assist a student in achieving a learning goal that would be beyond his or her abilities without help (Wood, Bruner, & Ross, 1976). Still, research on how to design computer-based scaffolding to facilitate and enhance college students' science problem solving remains a relatively new focus of study.

This paper offers a conceptual framework that identifies guidelines and strategies for future research on computer-based scaffolding in science problem solving. The following sections draw upon four areas of research. First, we analyze characteristics of science problems and the pertinent cognitive requirements for science problem solving. This review of the research also includes difficulties students have in solving science problems. Second, we review studies addressing how students have overcome difficulties in problem solving by utilizing computer-based scaffolding. Lastly, as a culmination of this review of the research, we propose a scaffolding framework that includes guidelines for designing computer-based scaffolding for science problem solving. We conclude with implications for instructional design for computer-based scaffolding and suggestions for future research.

Solving Complex Science Problems

Well-Structured or Ill-Structured Science Problems

Science problems can be described as well- or ill-structured depending on the properties of the problems (Hoskinson, Caballero, & Knight, 2013; Hsu, Brewe, Foster, & Harper, 2004; Jonassen, 2011). Most science problems in the real world are ill-structured and complex. Ill-structured problems typically consist of concepts, rules, and principles that have non-linear and interconnected relationships, delayed effects, and often include incompletely defined variables, such as incomplete information about the current situation and the desired outcome (Voss & Post, 1988). As a result, ill-structured problems do not have definitive problem-solving paths and straightforward answers; they often have many possible and acceptable solutions (Sterman, 1994). Some ill-structured problems are also socially and culturally mediated. Devising strategies to prevent the ecological destruction of a park is an example of a complex ecology problem; there are likely to be delayed effects and uncertain results depending on the unknown values of several variables; even the desired outcome state may be incompletely defined.

In contrast, most science problems that students face in formal educational settings are well-structured problems. Well-structured problems include complete and detailed information, specify a limited number of relevant rules and principles, and present clearly defined goals. Well-structured science problems involve a preferred solution process or a definite process to reach a single correct answer (Jonassen, 1997; Reid & Yang, 2002). Many physics and chemistry problems in educational contexts are quantitative and algorithmic in nature, requiring the application of formulae and equations. An example of a well-structured problem in chemistry is converting Fahrenheit to Celsius (see more examples in Shin, Jonassen & McGee, 2003). Students can solve this problem by using a simple formula. Well-structured problems also exist in genetics and molecular biology, such as determining an appropriate primer sequence when given a piece of double-stranded DNA. These are simple problems that require specific content knowledge and involve a definite problem-solving process to arrive at a correct answer.

Regardless of whether problems are well-structured or ill-structured, many college students consider science problems complex. Most ill-structured science problems (e.g., decision-making or design problems) are inherently complex, but many well-structured science problems can be considered complex due to the amount of available information, the number of variables, and the number and nature of interacting components (Taconis, Ferguson-Hessler, Broekkamp, 2001). Open-ended problems that allow multiple possible answers are more complex (and are more likely to be encountered in practice) than simple, formulaic ones that allow only one answer. Moreover, well-structured science problems that require prediction of consequences or outcomes (see examples in Lavoie, 1993), application in new contexts, evidence-based argumentation, or evaluation of possible solutions are more complex than routine problems requiring only recall of memorized knowledge or a simple algorithm (Hoskinson et al., 2013; see examples of higher-order questions in Lemons & Lemons, 2013). In sum, complex science problems, both well- and ill-structured, in physics, chemistry, geosciences, and biology differ in a variety of ways; however, all complex science problems require well-integrated knowledge and problem-solving skills to generate reasonable answers (NRC, 2012).

Cognitive Processes in Problem Solving

Because the findings regarding human problem solving in science education is consistent with the fundamental cognitive science literature, it is useful to review models and theories from cognitive science research as a theoretical basis for studying science problem solving. In particular, information-processing theories (IPT), which were adopted by developmental psychologists, seek to explain how humans solve problems (Newell & Simon, 1972). According to these theories, problem solvers should be able to (a) construct a representation or a *problem space* of the problem (i.e., initial states, goal states, and applicable operators) and (b) seek solution methods to reach the goal state (e.g., means-end-analysis). A problem solver's internal or external (e.g., in the form of text, graphic, or oral) representation summarizes his or her understanding of the problem (Novick & Bassok, 2005). Problem representation is critical in problem solving because it depicts the structure of the elements of the problem and the relationships between those elements as well as essential features of the problem. Seeking solution methods is an equally important process in problem solving. A solution method is the sum of the steps or processes to reach a solution. Metacognitive processes (e.g., being aware of a tendency to overlook certain things, checking for the kinds of mistakes made in the past, checking for misunderstanding, etc.) may be involved in the solution methods.

Problem solving is based on the interdependence between representation and solution methods. An accurate representation helps the problem solver determine which approach to the problem is appropriate and what steps they should take to solve the problem. As a result, a robust and productive representation of a problem can lead to a smooth and structured problem-solving process. Without an accurate representation, the problem solver may not find a solution method that works or may lose confidence in his or her ability to solve the problem.

Information processing theories were proposed to explain the problem solving process for mostly simple, well-structured problems, and thus, those models have limitations to explain the characteristics of solving ill-structured problems (Jonassen, 2011). Problem representation is critical for solving ill-structured problems. However, the problem space of most ill-structured problems is not clearly defined because of unclear initial and goal states and incomplete information (Ge & Land, 2004; Voss & Post, 1988).

Problem solvers have to generate necessary information and decide which information should be used. Moreover, because of the large number of elements in an ill-structured problem, they usually have broader problem spaces or a greater variety of possible problem spaces than well-structured problems. Therefore, to build a useful representation for an ill-structured problem, problem solvers may have to select a problem space or reduce the problem space by identifying sub-problems or sub-goals. It is easily assumed that, in the representation phase of solving an ill-structured problem, problem solvers may be required to have a greater degree of metacognitive abilities, including, for instance, the ability to articulate the problem space or monitor their choice of a problem space.

The solution approach or method may involve more or different kinds of skills, such as causal reasoning, building and testing hypotheses, and evaluating solutions, because one single correct solution is not available. For example, students in undergraduate introductory economics demonstrated more extensive arguments (e.g., justification of their claims) with ill-structured problems than well-structured ones (Cho & Jonassen, 2002). Problem solvers have to plan sequences of activities and steps to generate an answer and monitor those – specifying the problem space or understanding the question, forming a hypothesis, interpreting data, weighing evidence, reasoning from the data, drawing possible answers, and evaluating the answers

(Hoskinson et al., 2013; Li & Shavelson, 2001). Therefore, the solution method for ill-structured problems is typically more complicated than for well-structured problems.

To produce concrete solutions, problem solvers need to evaluate a number of possible solutions and then reason about each, searching for an optimal solution. Metacognition refers to a form of thinking about one's own thinking, which is the self-correcting nature of thinking, and allows learners to monitor their solutions as well as their problem solving processes (Swartz & Perkins, 1990). Metacognition is important in making appropriate decisions. Ill-structured problems require a greater degree of metacognition than others (Shin, Jonassen, & McGee, 2003). For example, the park design problem mentioned above might demand more metacognitive processing than a simple ecology problem with a fixed amount of information provided (see examples of simple and complex biology and physics problems in Hoskinson et al., 2013).

Science Problem Solving: Differences between Experts and Novices

In the last few decades, much educational research has focused on (a) differences between experts and novices when it comes to problem solving (e.g., Petcovic, Libarkin, & Baker, 2009) and (b) how individual students solve problems. Researchers have examined the problem-solving skills of experts as well as novice students in the disciplines of physics (Chi, Feltovich, & Glaser, 1981), chemistry (Sumfleth, 1988), and biology (Nehm & Ridgway, 2011; Simmons & Lunetta, 1993; Smith & Good, 1984). What they have found is that experts have the ability to represent the relevant complexities of the problem space of a problem and depict the structure of the elements of the problem as well as the relationships among those elements (Spector, Dennen, & Koszalka, 2006). Experts classify problems depending on details and *deep* features (Chi, Feltovish, & Glaser, 1981). Conversely, novices often represent the peripheral surface features of the problem and fail to include the main features of the problems (van Heuvelen, 1991). Novice representations are inherently simpler than those of experts, especially in terms of key variables and the connections among variables (Spector, Dennen, & Koszalka, 2006). Moreover, novices tend to spend less time building a representation of the problem than experts (Simon & Simon, 1978).

Experts' problem solving is precise, smooth and fast (Maloney, 1994; Nehm & Ridgway, 2011; Reif, 2008). A well-organized knowledge structure consisting of manageable units of concepts, rules, principles or theories helps experts systematically search for necessary information, effortlessly activate relevant information and, as a result, solve problems in an efficient way. On the other hand, novices demonstrate a lack of organization in their knowledge and skills (Smith, 1988). They usually make lots of errors in solving problems, which leads to slow problem solving. Novices reach a possible answer too quickly by relying on certain pieces of information provided in the problem, but without taking all of the information given into account (Taconis et al., 2001).

Metacognitive abilities are also considered essential for building precise solutions to problems (Tobias & Everson, 2000). Experts appropriately employ metacognitive abilities, such as planning, monitoring their problem-solving process, being aware of tendencies to overlook things, and evaluating their answers, when solving complex science problems (Singh, Granville, & Dika, 2002). In contrast, novice problem solvers are often unable to monitor their use of strategies.

Another difference between experts' and novices' problem solving is that across the science disciplines, novices often have naïve ideas about science content or only a superficial understanding of certain concepts related to problems (Tingle & Good, 1990). Considerable research on measuring students' levels of conceptual understanding and misconceptions in science disciplines has been conducted (Dirks, 2011). Students often hold misconceptions about many science concepts, such as evolution in biology (Nehm & Ridgway, 2011; Nehm & Schonfeld 2007), force in motion in physics (van Heuvelen, 1991), or meiosis in genetics problems (Wynne, Stewart, & Passmore, 2001).

Essential Knowledge and Skills for Science Problem Solving: A Conceptual Framework

As a summary of the previous research on problem solving, a conceptual framework for complex science problem solving is presented (see Figure 2.1):

a. Representation of the structure of major concepts, rules, and principles within a certain problem is important for interpreting problems appropriately (Chi, Bassok, Lewis, Reimann, & Glaser, 1989).
b. Representation of the problem situation or problem space (Heuvelen, 1991) and generation of a solution are interactive processes. Correct representation of a complex science problem influences the search for solution methods. Conversely, while generating a solution, the problem-solver may change his/her initial representation of the problem.
c. Procedural knowledge is required to reach a solution in a systematic way..
d. In-depth content knowledge is also necessary for science problem solving (Reif, 2008; Shin, Jonassen, & McGee, 2003). The level of domain knowledge may influence reasoning as well as confidence in solving problems.
e. Lastly, metacognitive skills are required to plan problem solving in advance, notice where errors are made by constantly monitoring the problem solving process, and evaluate answers to generate the best one (Azevedo, 2005; Flavell, 1979; Kitchener, 1983).

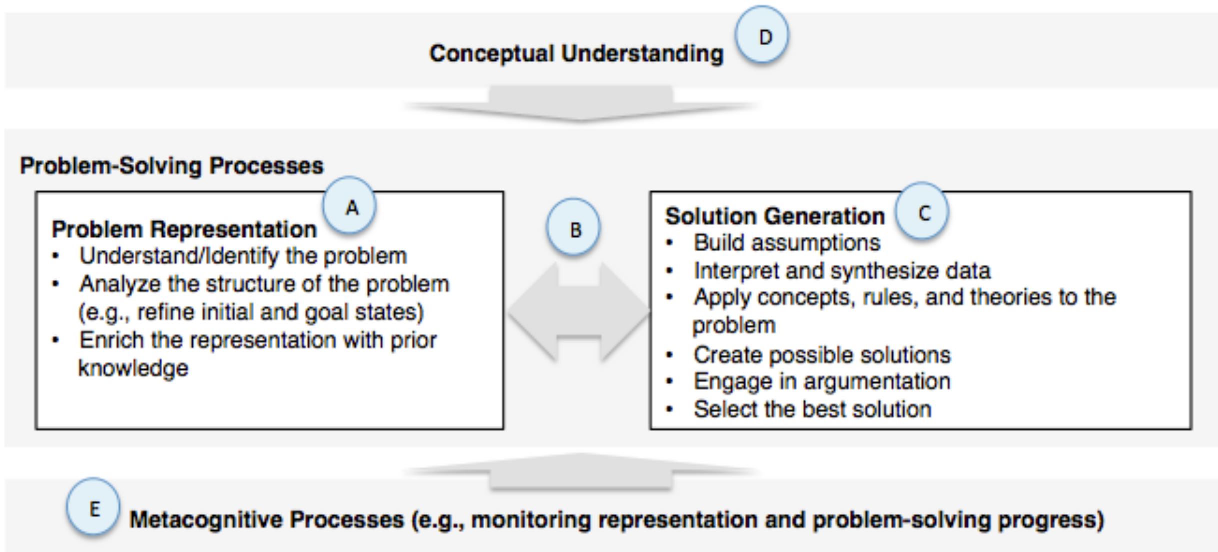

Figure 2.1. Conceptual framework for complex science problem solving

Since different types of science problems in different disciplines require a wide range of cognitive skills and knowledge (e.g., Hoskinson et al., 2013), it is difficult to conceptualize science problem-solving processes. However, identifying general problem-solving processes, which are applicable to most complex science problems, may help inform the design of instructional strategies for novice students' science problem solving. In the following section, we present the results of our review and analysis of theoretical and empirical literature on scaffolded instruction for complex problem solving from educational technology, the learning sciences, and science education.

Scaffolds for Supporting Complex Science Problem Solving

Definition of Scaffolding

Many students need instructional guidance or support during science problem solving because of the complexity of science problems. In the community of instructional design and learning environments, instructional supports are known as scaffolds (Palincsar & Brown, 1984).

Scaffolds can be provided by a teacher or advanced peer to assist a learner in solving a problem or attaining a learning goal that would be beyond his or her ability without support (Wood, Bruner, & Ross, 1976). There are four distinct types of scaffolds that can help students be successful at learning: conceptual, metacognitive, procedural, and strategic (Hannafin, Land & Oliver, 1999). These four types of scaffolds can support students as they build representations of the problem space, perform problem-solving processes and evaluate possible solutions. Conceptual scaffolding helps students consider what elements pertain to the problem and understand important concepts in certain domain contents (e.g., Linn, 2000). Metacognitive scaffolding helps students in planning, monitoring, and evaluating their problem solving (Azevedo, 2005; Quintana, Zhang, & Krajcik, 2005). Though metacognitive scaffolding is designed mostly to encourage students to employ metacognitive processes, reflection and critical thinking may influence the depth of a student's conceptual understanding or lead to an effective problem solving processes. Procedural scaffolding offers guidance in utilizing resources to solve a problem or make progress. Strategic scaffolding offers guidance in considering alternative approaches during the execution of the steps to reach a solution. Most problem-solving processes need a combination of these four types of scaffolds.

Computer-Based Scaffolding Approaches

Over the past few decades, computer-based instruction has become more common in educational settings. Scaffolds on paper or computer are called hard scaffolds; in contrast, soft scaffolds refer to support from humans (Saye & Brush, 2002). Hard scaffolds are often described as fixed without fading (e.g., a standard computer-based instructional system; CBI), which means students receive predetermined types and amounts of scaffolding regardless of their progress; soft scaffolds are usually considered more adaptive to the progress of the student (Pea, 2004). Researchers in the fields of science education, instructional technology, and learning science focus on how to design computer-based scaffolding that is beneficial for improving students' learning, including problem-solving processes. However, only a limited number of research studies have systemically investigated the effects of computer-based scaffolded instruction across the science disciplines at the undergraduate level (unlike K-12). For example, a study by Singh and Haileselassie (2010) demonstrated the impact of Web-based tutorials on the development of college students' quantitative and conceptual problem-solving skills in physics. The tutorials were designed based on the cognitive apprenticeship model – coaching, modeling, and scaffolding (Collins et al., 1989). The tutorials, related to introductory mechanics, electricity, and magnetism, were designed to provide "a structured approach to problem solving" (p. 43). Each tutorial first provides an overarching complex problem, then several sub-problems of the overarching problem in multiple-choice format. Incorrect answers are connected to help sessions on the misunderstood topic. Then, students respond to problems in different contexts to reflect on what they learned. Lastly, students are given paired problems that use similar physics principles but are presented in a different context without additional support (faded scaffolding). The results of their preliminary study showed that students' reasoning in physics improved after using the faded computer-based scaffolding.

The most common computer-based scaffolding to support problem-solving includes: (a) question prompts (Zellermayer, Salomon, Globerson, & Givon, 1991) with/without feedback; (b) expert models (Spector, Dennen, & Koszalka, 2006); (c) visual/graphical aids via structured templates or mapping tools (Belland, 2014; Lajoie, 2005; Reiser, 2004); (d) simulations to show scientific phenomena visibly or conduct virtual experiments (van Joolingen 1999); and (e) feedback on student performance (Lepper, Drake, & O'Donnell-Johnson). Question prompts are simply instructional support designed to guide a student's thinking and help him or her activate relevant schema or cognitive processes (Scardamalia & Bereiter, 1985). Question prompts can be provided independently or combined with feedback. Feedback is a response to a student's answer or performance (Mason & Bruning, 2001). In most cases, feedback helps convey two different types of information, for verification and elaboration (Kulhavy & Stock 1989). Verification feedback helps students identify whether their answers or performances are accurate. Elaboration feedback provides more guidance, hints, and relevant information on why the selected answer is correct or the other choices are incorrect. Providing an expert model is another scaffolding mechanism that shows how experts perform a certain complex task. Expert models are typically procedural or strategic but may also have conceptual and metacognitive aspects. Scaffolding can be delivered via visual or graphical aids for indicating important processes of a problem (Belland, 2014). Visual aids in the form of templates (e.g., charts, diagram, tables) to follow or fill in can constrain the problem-solving process. Visual aids make the proper sequence of problem solving explicit and can compel, or at least encourage, students to follow the prescribed sequence of activities, which are small and more manageable than the complex, whole problem. A simulation in the context of education refers to the use of a computer program to model a dynamic object, phenomenon, system or a process that usually is not easily observable (de Jong & van Joolingen, 1998; Akpan, 2001). Simulations have been used in physics, biology, chemistry, and other science disciplines for mainly two purposes: modeling phenomena and creating interactive virtual laboratories for experiments and hypothesis testing (Scalise et al., 2011).

Personalized/Adaptive Scaffolds

A question that remains to date is: What types and what amount of scaffolding are appropriate for students who have different levels of cognitive skills and prior knowledge? Providing the same scaffolding to all students regardless of their learning level may result in marginal learning gains. We can generally assume that lower-performing students possess limited prior knowledge and have more difficulties with science problem solving so that they are likely to need more scaffolding than higher-performing students. For example, lower-performing students may benefit more from immediate feedback for verification and elaboration to correct their misconceptions. But, they may experience frustration with metacognitive types of scaffolding that does not directly address their difficulties and may cause cognitive load. Therefore, we need to consider how to avoid lower-performing students' cognitive load from too much scaffolding. On the other hand, high-performing students may need a smaller amount of feedback to find a correct answer, and they may use metacognitive types of scaffolding more successfully that encourages them to reflect on their answers on their own. For example, while supportive modeling may be more effective for higher-performing students, mandatory step-by-step visual guidance with immediate feedback may be more effective for lower-performing students.

A related consideration to cognitive skills and prior knowledge is students' experience of the types and amount of scaffolding needed. For example, at some levels (e.g., early K-12) students may not have the cognitive skills appropriate for problem solving without constant scaffolding. On the other hand, adults with considerable prior knowledge and higher cognitive skills may find too much scaffolding limiting to their learning process. As we continue to explore the problem solving process, the experience and level of the learner needs to be considered.

Computer-based scaffolding has limitations to supporting a variety of students with different needs, in opposition to highly dynamic scaffolds from a teacher's one-on-one instruction (Azevedo & Jacobson, 2008; Saye & Brush, 2002). However, based on the results of initial and regular diagnoses of students' levels of knowledge and skills during problem solving, computer-based programs may be able to suggest or (partially) tailor/adapt types and amount of scaffolding to each student. Otherwise, based on the diagnosis, the programs determine the amount of learner control so that higher-performing students can be allowed to select their computer-based scaffolds.

In addition, how to fade scaffolding should be considered crucial to design effective scaffolding in science instruction (Lyons, 2011; McNeill et al., 2006; Pea, 2004). The concept of fading support as students make progress has been promoted in the literature since Collins and colleagues (1989) developed the instructional approach called cognitive apprenticeship. Fading is important, because scaffolding does not merely support students' deficient skills in a certain learning context; scaffolding should allow students to internalize skills so that students can solve similar or advanced problems without scaffolding in the end. However, such fading is difficult to design and implement in computer-based scaffolds. Computer-based instruction (c.f., an intelligent tutoring system) has only been successful with limited fading of problem-solving scaffolds in well-defined domains (Belland et al., 2008). Further research is required to determine if the concept of fading is feasible in computer-based instruction.

Closing Thoughts about Computer-Based Scaffolding

Over the past 20 years, significant consideration has been given to the difficulties students have in solving science problems. The growing number of research studies regarding computer-based scaffolding shows some evidence that computer-based scaffolding can be successfully used to help improve learning in biology, chemistry, engineering, and other science fields. Computer-based scaffolding can facilitate students' understanding of important science concepts and principles, and allow students to engage in problem-solving processes. The focus of the next section is identifying how to design computer-based scaffolds to facilitate science problem solving based on our review of previous research studies on scaffolding for problem solving.

Guidelines for a Computer-Based Scaffolding Design for Science Problem Solving

This section presents guidelines, which are drawn from the review and analysis of previous theoretical and empirical research studies, to help instructional designers and educational practitioners design computer-based scaffolding that will address students' deficiencies in science problem solving and enhance their problem solving skills. Table 2.1 provides a summary of scaffolding guidelines and computer-based scaffolding strategies for science problem-solving processes.

Table 2.1.
Scaffolding guidelines & computer-based scaffolding strategies for science problem solving

Guidelines	Scaffolding strategies
Enhance the conceptual understanding (conceptual scaffolds)	• Prompt students to express their understanding of important concepts and notice their misconceptions (e.g., Chang & Linn, 2014; Linn, 2000). • Provide support for correcting misconceptions (e.g., Reif & Scott, 1999). • Embed support for students to manipulate relevant elements/parameters of scientific concepts or phenomena (e.g., Korkmaz & Harwood, 2004). • Enable students to apply scientific concepts to problems/situations (e.g., Frailich, Kesner, & Hofstein, 2009).
Help students articulate problem representation	• Prompt students to explain deep features of the problem space (relevant factors, information, and constraints related to the problem) (Chi, Bassok, Lewis, Reimann, & Glaser, 1989; Ge & Land, 2003). • Provide support for practicing self-explanation (e.g., Conati & VanLehn, 2000). • Embed support for students to externalize and articulate the problem space using different representation tools.
Guide disciplined problem solving	• Embed guidance about approaches to reach a solution (e.g., Singh & Haileselassie, 2010). • Provide support for students to pay attention to important problem-solving processes (Belland, Glazewski, & Richardson, 2011). • Prompt students to engage in argumentation (Jermann & Dillenbourg, 2003) and reasoning (Graesser, Swamer, Baggett, & Sell, 1996).
Encourage students to plan, monitor, and evaluate problem-solving processes (metacognitive scaffolds)	• Prompt students to plan, monitor, and evaluate sequences of problem solving (e.g., Land & Zembal-Saul, 2003; Lin & Lehman, 1999) • Provide support for explaining why experts perform a particular task in problem solving (van Merrienboer & Kirschner, 2007).

Design of Scaffolds that Enhance the Conceptual Understanding

Most science concepts are difficult for students to understand; they are abstract, symbolic or not observable. In turn, many students have difficulty understanding new science concepts. Moreover, many students hold partially correct understandings or misconceptions about science that are resistant to change. Therefore, it is important to have students consciously notice their own misconceptions as well as to teach new concepts efficiently. Also, partial understanding should be elaborated on or moved to a deeper level of understanding that promotes efficient problem solving.

Computer-based scaffolding can lead students to reorganize their knowledge, express their understanding of concepts (prior knowledge) explicitly, identify their misunderstandings or partially correct understandings, and build up new correct, integrated understandings. Different types of scaffolds can be used for students to obtain a better understanding. Conceptual question prompts for self-explanation can be combined with immediate feedback to help students correct their misconceptions. Immediate feedback is effective for the acquisition of domain knowledge (Koedinger & Corbett, 2006). Students may distinguish between their own understanding and an expert's understanding using expert models. Simulations can contribute to an enhanced understanding of complex science concepts (e.g., molecular interaction) by providing opportunities to apply those concepts to real-like situations (Schank & Kozma, 2002). But, simulations should probably be combined with other scaffolding to maximize the educational benefits (Chang & Linn, 2014).

Design of Scaffolds that Guide Disciplined Problem Solving

Many students' science problem-solving processes are not organized (Chi et al., 1981). Reasoning skills are important to execute efficient science problem-solving processes and reach correct or sound solutions. However, many college students lack reasoning skills to solve science problems (Nehm & Ridgway, 2011). Many students have difficulty producing reasonable solutions supported by appropriate evidence (von Aufschnaiter, Erduran, Osborne, & Simon, 2008). Thus, students need support to improve their problem-solving processes. Scaffolding can be used to facilitate phases of science problem solving, such as constructing hypotheses, explaining evidential relationships between the data and hypotheses, and justifying solutions (Hui-Ling, 2010). Scaffolds can be delivered through question prompts, graphic guidance or expert models. Question prompts oriented toward procedural guidance provide students with procedure suggestions at the moment of need, which is crucial for generating solutions or answers. For example, a question prompt such as "What evidence is there to support the contention that…?" requires students to seek evidence to support their own answers (Jonassen et al., 2009). Expert models also provide procedural guidance with regard to how experts solved or approached a problem (Spector, Dennen, & Koszalka, 2006). Expert models can be combined with question prompts to show students how to approach the problem. Visual step-by-step guidance can also be used as procedural support, but it has limitations because students tend to follow the steps without reflection. Therefore, it can be combined with metacognitive support.

Design of Scaffolds that Help Students Articulate Problem Representation

Many students have difficulties with the representation of their problem space. Therefore, it is important to teach students how to represent and articulate their problem space. Previous research shows that both question prompts and graphic aids demonstrate some educational benefit for representation. Question prompts can direct students' attention to important aspects of the problem space at the beginning of the problem-solving process (King & Rosenshine, 1993). For example, a question prompt like, "what do you think are the primary factors of this problem?" (Ge & Land, 2003) can encourage students to identify relevant factors, information, and constraints related to the problem. Question prompts can also help students to activate relevant existing problem schema resulting from previous experience, intentionally link their existing problem schema to the current problem, and manipulate the schema to fit the problem. Graphical aids, like concept mapping tools, can also help students present their implicit problem space by creating artifacts like maps, including nodes and links. In addition, representation scaffolding can be delivered through a modeling mechanism. A study by Conati and VanLehn (2000) indicates that the *SE-Coach* in an intelligent tutoring system, which was designed for teaching self-explanation with worked-out examples, helped college students enhance their cognitive skills in physics (Conati & VanLehn, 2000). Students should be able to make progress in their representations. Therefore, continuous support for representation is required to help students articulate and elaborate on their initial representation.

Design of Scaffolds that Encourage Students to Plan, Monitor, and Evaluate Problem-Solving Processes

Metacognition helps students be aware of their knowledge (e.g., what I know or do not know to solve this problem) and problem-solving processes. Metacognition helps students make fewer errors in problem solving (Lin & Lehman, 1999). Unfortunately, many students lack a natural tendency to think reflectively about their knowledge and skills when problem solving; rather, they tend to rush to find a correct answer. In most cases, applying conceptual knowledge to a problem is required, but metacognitive processes are not an apparent requirement in problem-solving processes. Consequently, many students often do not value time-consuming and unclear metacognitive processes; only a few students perform metacognition consciously and spontaneously. Thus, there should be structured practice within the curriculum, where the central aim is to teach students how to use metacognition to solve problems and to strengthen and internalize metacognitive skills. Metacognition is considered domain-general or independent. Theoretically, if metacognition is internalized through solving a problem in a context with metacognitive support, it should be transferrable to other problems in different contexts (Brown, Bransford, Ferrara, & Campione, 1983).

Metacognitive scaffolds have been provided in the form of question prompts that elicit students' self-monitoring and reflection (Ge & Land, 2003). Question prompts can ask students to plan, monitor and evaluate their problem solving (Ge & Land, 2003; Rosenshine, Meister, & Chapman, 1996). These questions lead students to express their own metacognitive thinking. Lin and Lehman (1999) conducted a study on how a computer-based simulation program helps college students learn how to control variables in biology by designing and conducting experiments. The main strategy used in the simulation program was a presentation of prompts to help students learn about strategies for controlling variables. Students received different types of prompts: reasoned, rule-based, or emotion focused. The results show that students provided with reasoned justification prompts (e.g., why employ the experimental design principle and strategy?) were more reflective of their actions as they conducted experiments and engaged in metacognitive thinking than were other students who received alternate prompts (e.g., how are you feeling about yourself right now?).

It is generally accepted that metacognition support from humans is more effective than that from computers (Belland et al., 2008). However, computer-based metacognitive scaffolding may be successfully combined with human support for metacognition. Computer-generated metacognitive scaffolding can be considered unnecessary or easily ignored by students, as it does not have immediately recognizable benefits. Students might need to realize the possible benefits of their metacognitive activities first. Thus, computer-based metacognitive support should be designed very carefully if teachers are not available to provide this kind of support. Roll and his colleagues (2007) suggest that metacognition support should be embedded in problem-solving contexts and combined with the case where students give a wrong answer, as they may give more attention to metacognitive hints.

Summary

The recognition of students' difficulties in science problem solving and inquiry about how to improve students' problem-solving skills has led to the design of deliberate and effective instructional practice to help students become better problem-solvers. The present paper reviewed and summarized previous research studies presenting empirical evidence of the effects of various computer-based scaffolding on science learning. The results of our review indicate that computer-based scaffolding has the potential to improve science problem solving. The framework in this paper proposes a set of guidelines to assist and guide instructional designers in designing effective computer-based scaffolding for problem solving skills. Further, we expect that this framework will contribute to the development of students' problem solving skills. As this conceptual framework is primarily based on theory and limited empirical research, these guidelines require further empirical validation studies to determine if they hold up as expected when implemented. It is essential to identify how students actually use scaffolding while they engage in problem solving; its actual use may differ from its intended use.

Limitations of this study and suggested future research

This study has a few limitations. First, this review does not consider scaffolding from humans. Researchers emphasize appropriate use of both human and computer scaffolding (Belland, 2014; Tabak, 2004). Particularly, Tabak (2004) calls this “synergetic scaffolding.” We need to consider that teachers perform in supportive roles to make computer-based scaffolding fruitful. Second, this paper does not address students’ motivation. Motivation influences problem solving in learning contexts (Belland, Kim & Hannafin, 2013). Motivated students may be more engaged in problem-solving tasks. Third, this paper does not provide clear principles for combining different types of scaffolding for a synergetic effect on science problem solving. Providing a single type of scaffolding in computer-based instruction may have limitations in teaching necessary cognitive skills in science problem solving, but it is challenging to identify the most effective scaffolding for all students and the factors of the interaction between different types of scaffolding that create synergetic effects. We need systematic research on how to combine different types of scaffolds to support science problem solving and refine the ways in which various computer-based scaffolding is used.

As most research studies on computer-based scaffolding have been conducted in K-12 contexts, educational researchers need to determine what factors make scaffolding effective in college science classes. The relationship between different types of computer-generated scaffolding and the meta/cognitive skills of adult learners has not been sufficiently studied. We also need to study how the students’ level of cognitive skills and prior knowledge influence their actual use of scaffolding. Lastly, each science discipline has distinctive features; namely, science problems in biology and physics have very different characteristics (along with some similar aspects). Therefore, it would be interesting to examine how the suggested guidelines in this paper work in various science disciplines, which could lead to an understanding of factors that influence the design of effective computer-based scaffolding in each science discipline.

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CHAPTER 3

STUDENTS' USABILITY EVALUATION OF A WEB-BASED TUTORIAL PROGRAM FOR COLLEGE BIOLOGY PROBLEM SOLVING[2]

[2] Kim, H. S., Prevost, L., & Lemons P. P. Submitted to *Journal of Computer Assisted Learning*

Abstract

The understanding of core concepts and processes of science in solving problems is important to successful learning in biology. We have designed and developed a Web-based, self-directed tutorial program, *SOLVEIT* that provides various scaffolds (e.g., prompts, expert models, visual guidance, etc.) to help college students enhance their skills and abilities in solving biology problems. This paper details the features of *SOLVEIT* that are contextualized within the biological domains of evolution and ecology. A qualitative case study was conducted to evaluate the usability of the program. A small number of students were recruited from an introductory biology course at a large public university in the Southeastern United States. Data for this study were collected through the *SOLVEIT* database, semi-structured interviews and an online survey. The findings of this study demonstrate the potential of the program for improving students' problem solving in biology. Determining the impact on more general scientific investigation skills in experimental research contexts was beyond the scope of this effort. Implications for improving *SOLVEIT* are discussed. This study also provides some guidance for researchers and practitioners who are interested in the design, development and evaluation of Web-based tutorial programs in science education.

Introduction

College science courses should enable students to gain understanding of the major organizing concepts of a discipline and problem-solving skills that facilitate use of evidence to explain and predict diverse scientific phenomena (Hoskinson, Caballero, & Knight, 2013; National Academy of Science [NAS], 2011; National Research Council [NRC] 2012). It is challenging to meet these goals in college science courses. For the past few decades, science education researchers and practitioners have placed much emphasis on students' problem-solving performance and suggested many innovative teaching methods to help students engage in problem solving, but deficiency in problem-solving skills is still a core problem in science education (NRC, 2012).

College students struggle with solving science problems for several reasons. First, many students hold misconceptions about the key concepts involved in a problem (e.g., evolution, force in motion, meiosis, etc.), naïve ideas about science content, and unscientific knowledge (Nehm & Ridgway, 2011; Nehm & Schonfeld, 2008; van Heuvelen, 1991). Second, students tend to solve problems using weak or ineffective problem-solving processes. For example, in chemistry, students tend to use algorithms without a deep understanding of the major concepts underlying the problems (Gabel & Bunce 1994). In physics (Chi 1981; Maloney 1994), biology (Nehm & Ridgway 2011) and chemistry (Sumfleth 1988) research has shown that students use superficial clues instead of employing advanced problem-solving processes (e.g., evaluating possible assumptions). Third, students are often unwilling to take opportunities to respond to challenging problems. It is not only weak or improperly trained students who avoid complex problem solving; it is part of human nature to seek simple solutions (Spector, 2012). A particular challenge in science education and in education in general is to help students become more willing to take opportunities to respond to challenging problems and situations.

Scaffolded instruction can promote the development of problem-solving skills (Belland, 2010; Eslinger, White, Frederiksen, & Brobst, 2008). Traditionally, the term *scaffolding* referred to the support or guidance offered by a teacher or an advanced peer to assist a learner in making progress through a learning sequence (Vygotsky, 1978; Wood, Bruner, & Ross, 1976). More recently, the scaffolding concept has widened to include the use of computer-based support to help students learn (e.g., Belland, 2014; Hill & Hannafin, 2001; Saye & Brush, 2002; Sharma & Hannafin, 2007). Computer-based scaffolding can provide practice and help students focus on important problem-solving processes (Reiser, 2004). More specifically, scaffolding provides supports and guidance for students that function conceptually, strategically, metacognitively, or procedurally (Hannafin, Land, Oliver, 1999; Hill & Hannafin, 2001). Conceptual scaffolding helps students consider what elements pertain to the problem and understand important concepts in certain domain contents (e.g., Linn, 2000). Strategic scaffolding assists with how to approach a problem to reach a solution. Metacognitive scaffolding helps in planning, monitoring, and evaluating their problem solving (Azevedo, 2005; Quintana, Zhang, & Krajcik, 2005). Procedural scaffolding is guidance about how to utilize provided resources and tools (e.g., website maps).

Scaffolding via Web-based technologies can be used in college education to facilitate students' understanding of course content, teach important concepts and principles, and allow students to engage in problem-solving processes (e.g., Carmichael & Tscholl, 2011; Oh & Jonassen, 2007). For example, in physics, a study by Singh and Haileselassie (2010) demonstrated the impact of self-paced, Web-based tutorials on the development of college students' quantitative and conceptual problem-solving skills. The tutorials, related to introductory mechanics, electricity, and magnetism, are designed to provide "a structured approach to problem solving" (p. 43) employing modeling, coaching, and scaffolding strategies as students solve complex quantitative physics problems. The results of their preliminary study showed that students' reasoning was improved after using the tutorials.

Research studies regarding biology problem solving and the effectiveness of instructional interventions on students' problem solving skills are sparse (Dirks, 2011), partly because biology education research is an emerging field (Dirks, 2011; NRC, 2012). It appears that no computer-based scaffolds are available to strategically teach problem solving in introductory college biology courses. It is clear that most computer-based tutorial programs developed for physics and chemistry cannot be directly applied to biology learning contexts because of the specificity of the domain tools and the limited flexibility of their use. Accordingly, biology education researchers need to place more emphasis on designing and implementing instructional interventions, including computer-based tutorials, to enhance college students' knowledge and skills for solving biology problems.

We built a scaffolding design framework (Kim & Spector, in preparation) grounded in the literature on computer-based scaffolding (Belland, Glazewski, & Richardson, 2008; Hannafin, Land, & Oliver, 1999; Saye & Brush, 2002). Informed by the design guidelines in the scaffolding framework (e.g., guide disciplined problem-solving processes using procedural and strategic scaffolds), we designed and developed a Web-based, self-directed program, *SOLVEIT*. The program was designed to support the development of college students' problem-solving skills within the biological domains of evolution and ecology. This program includes three biology problems, takes students through the scientific problem-solving process to draw a conclusion, and provides scaffolds for problem solving (e.g., prompts, immediate feedback, expert models). In the next section, we first describe the features and functions of *SOLVEIT* in detail. We then present a qualitative case study about *SOLVEIT* usability and student learning.

Web-Based Tutorial Program: *SOLVEIT*

We built *SOLVEIT* using the open source technologies *PHP* and *MySQL* in Fall 2011. As we developed *SOLVEIT*, we repeatedly reviewed its visual design (e.g., font size, screen layout), content (e.g., accuracy of expert answers, clarity of question prompts), instructions, and guidelines; improvements were made accordingly.

Problems

SOLVEIT includes two problems on evolution and one on ecosystems. The first two problems require knowledge of species concepts (e.g., Campbell et al., 2008) and the use of data to draw conclusions about the species relationships of: (1) Scrub Jays in the Eastern and Western United States and on Santa Cruz Island (modified from BirdLife International, 2014), and (2) Benthic and Limnetic Sticklebacks in British Columbia's Paxton Lake (McPhail, 1992). The third problem requires knowledge of ecological interactions (e.g., Campbell et al., 2008) and the use of data to draw conclusions about the ecological interaction between *Phorbia* flies and the fungus *Epichloë* (modified from Bultman & White, 1988; Bultman, White, Bowdish, Welch, & Johnston, 1995; Bultman, Welch, Boning, & Bowdish, 2000).

Scaffolding Phases

SOLVEIT has six phases for each problem (see Table 3.1). The six phases of *SOLVEIT* include: (1) define concepts, (2) construct an initial answer, (3) assess problem-solving skills, (4) check and revise initial answer, (5) reflect on and describe problem-solving skills, and (6) evaluate experts' solutions to the problem. Students are given different types of scaffolds in each phase: (1) conceptual scaffolds via question prompts and immediate feedback, (2) strategic scaffolds via experts' models and interactive tutorials, (3) procedural scaffolds via visual guidance, and (4) metacognitive scaffolds via question prompts, a checklist, and experts' models.

Table 3.1.

Phases and scaffolds of SOLVEIT in each problem

Phase	Student Activity	Scaffolding Type	Scaffolding Strategy
1	Define important concepts related to the problems	Conceptual	Prompts
2	Construct an initial argument/answer	Conceptual and Strategic	Prompts
3	Engage in the scientific process (e.g., interpreting data, evaluating possible conclusions)	Conceptual, Strategic and Procedural	Prompts, immediate feedback, interactive tutorials and visual guidance
4	Revise the initial argument/answer	Metacognitive	Prompts and checklist
5	Reflect on thinking skills	Metacognitive	Prompts
6	Evaluate expert's answers	Strategic and Metacognitive	Expert models

Phase 1 is intended to help students revisit and explain important concepts used in the problem, providing *conceptual scaffolding*. For example, students are prompted, "We've learned species concepts in class. Without using your notes, explain what species concepts are, and define each concept we discussed using your own words." These kinds of questions were designed to activate and retrieve students' prior domain knowledge. Deep conceptual understanding is necessary to solve complex science problems (Shin, Jonassen, & McGee*,* 2003). Previous research studies show the positive impact of question prompts on conceptual understanding (Chen & Bradshaw, 2007).

Phase 2 is intended to help students represent their knowledge explicitly and focus on constructing well-structured answers, thus giving the students a combination of *conceptual and strategic scaffolding*. Good problem solvers pay attention to obtaining sophisticated solutions to problems (Schoenfeld & Herrmann, 1982). Chi and her colleagues (1989) emphasize the importance of *think-aloud* in science learning. In *SOLVEIT*, students are prompted to generate a claim, support the claim with evidence, evaluate the adequacy of the evidence, and establish conclusions. For example, students are prompted, "Your answer should include a claim – a statement of whether the Island, Western, and Eastern Scrub Jays are the same or different species; evidence - an analysis of the data that support your claim; and reasoning – a statement of how the evidence is connected to your claim based on different species concepts." According to Toulmin (1958), an answer or argument can be considered strong if it contains certain components (i.e., claims, data, warrants, backing, qualifiers, and rebuttals). Due to the difficulties in distinguishing between the interrelated components of the Toulmin's model, a modified model that includes claim, evidence, and reasoning is used to help students to build reasonable solutions. A similar method has been used previously (Speth et al., 2010).

Phase 3 is intended to help students engage in the problem-solving process using *procedural and strategic scaffolding*. Students respond to a series of multiple-choice questions that help them with clarifying the problem, analyzing scientific data, examining possible assumptions and drawing a conclusion. For example, students are prompted, “Based on the biological species concept, what conclusion can we draw about the species relationships of the Western and Eastern scrub jays?” These kinds of question prompts were designed to help students employ adequate problem-solving processes in order to solve the problem. When students respond incorrectly to the questions, *SOLVEIT* automatically provides immediate, elaborated feedback with an explanation of why the answer chosen is incorrect (see Figure 3.1). Phase 3 also links to additional interactive tutorials about how to: (1) analyze scientific data, (2) draw conclusions based on data, (3) read and interpret tables and graphs, and (4) build assumptions. If students respond incorrectly to particular questions, they are automatically linked to the interactive tutorials that address their error(s) (see Figure 3.2). Previous research studies show guidance is necessary to help students’ problem-solving processes, such as constructing hypotheses and explaining evidential relationships between data and their hypotheses (Wu & Pedersen, 2011).

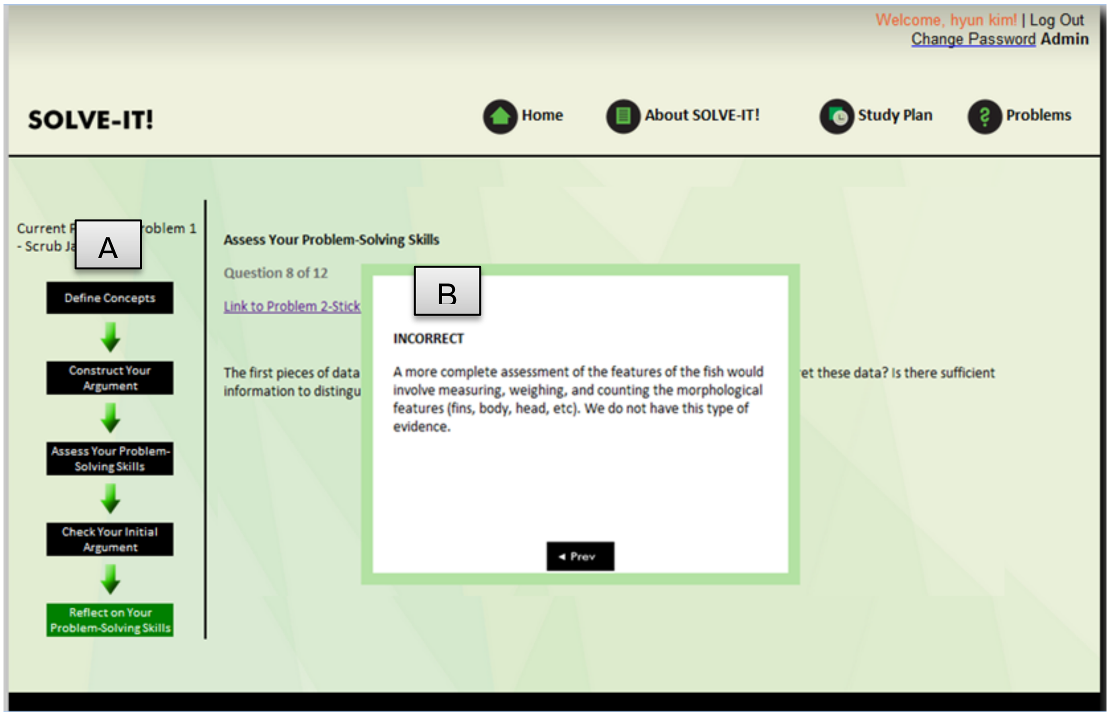

Figure. 3.1. Screenshot of Phase 3 of *SOLVEIT.* (a) Procedural scaffold – visual guidance to show the different phases in each problem. (b) Strategic scaffold – question prompts and immediate feedback to guide how to approach the problem.

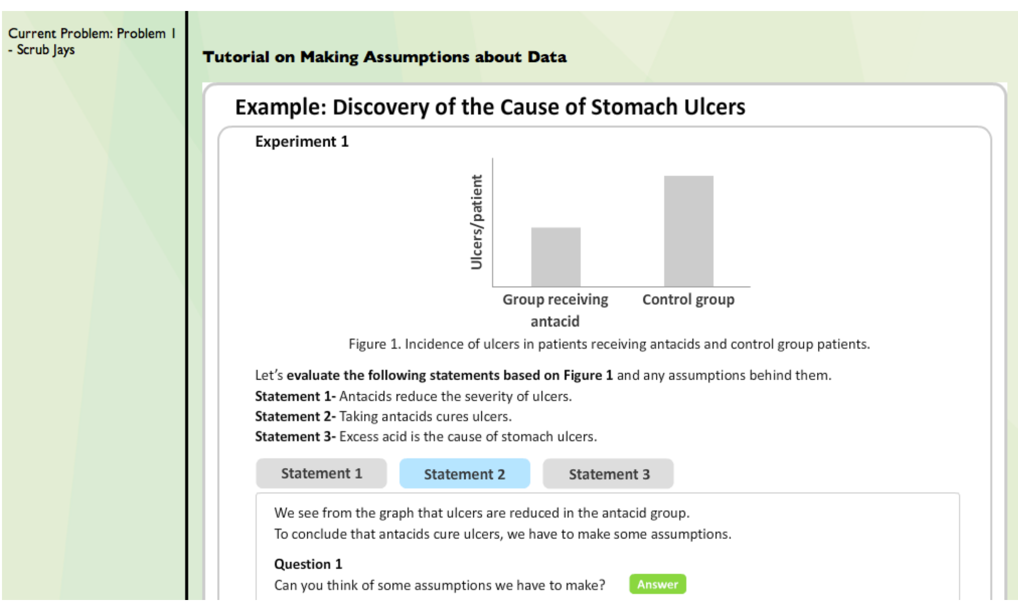

Figure. 3.2. Screenshot of one of the interactive tutorials in Phase 3 of *SOLVEIT*. The "Making Assumptions" interactive tutorial shown here was inspired by Hannam & Hagley, 2008.

Phase 4 is intended to help students come up with final answers. In this phase, each student is presented with the prompt, "This is your initial response to the problem. Would you like to revise your answer? If so, do so in the box below?" The intent of this prompt, which provides *metacognitive scaffolding*, is to encourage students to reflect on their initial solutions and revise, elaborate, or create a new solution. Phase 4 also provides a checklist, e.g., "Is there sufficient evidence to support this claim?" The checklist was also designed to encourage students to reflect on their cognitive processes. Metacognitive support in the study of Ge and Land (2003) positively influenced on eliciting students' self-monitoring and reflection.

Phase 5 is intended to help students reflect on their own thinking skills and what kinds of skills are required to solve complex science problems, providing *metacognitive scaffolding*. Students are asked to name and explain the problem-solving processes needed to solve the problems in *SOLVEIT*. For example, students are prompted, "What are the important problem-solving skills you needed to solve Problem 2?" These kinds of questions were designed to enhance students' metacognitive abilities.

Phase 6 is intended to help students reflect on the expert's solutions (see Figure 3.3). This phase gives students opportunities to identify differences between their answers and an expert's answer and to evaluate those answers themselves, providing *metacognitive and strategic scaffolding*. Expert models in *SOLVEIT* were designed to demonstrate how to analyze the provided data and use the data to draw a conclusion. Expert models provide guidance with regard to how experts solved or approached a problem and can help students' problem solving performance (Spector, 2006).

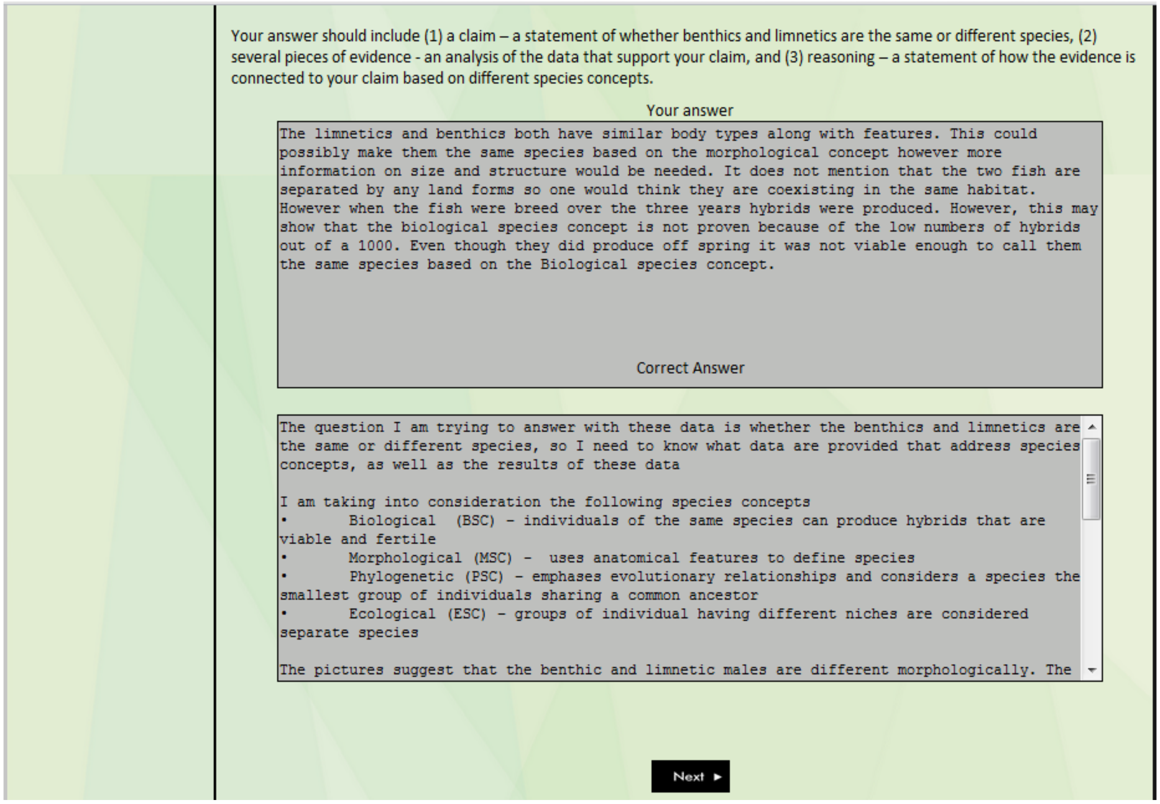

Figure. 3.3. Screenshot of the experts' model in the review session of *SOLVEIT*.

In the next section, we present the methods, results, and implications of our research study to evaluate *SOLVEIT* usability, including areas of future research.

Methods

Here we address two research questions about *SOLVEIT* usability and student learning: (1) How do students use and evaluate *SOLVEIT*? and (2) What do students perceive as learning gains from completing *SOLVEIT*?

To gather data to answer the research questions, we conducted a non-experimental, descriptive case study focusing on individual students (Yin, 2003). Descriptive case studies are often used to illustrate a phenomenon or event within its specific context (Merriam, 1998; Yin, 2003). This descriptive case study focuses on describing students' interactions with *SOLVEIT*.

Setting and Participants

The study was conducted in the spring semester of 2012 in an introductory biology course, *Organismal Biology*, at a large public university in the Southeastern United States. Among the 37 students, ranging from freshmen to seniors, who volunteered to participate in this study and who completed *SOLVEIT*, a sample of 6 students was selected through maximum variation sampling (Patton, 2002) for this case study. We maximized sample variation using the following criteria: gender, major, years of study in college, and level of scientific literacy skills (SLS) as measured by the Test of Scientific Literacy Skills (TOSLS) (Gormally, Brickman, & Lutz*,* 2012). The TOSLS has a maximum possible score of 28. The range of scores among all students in BIOL 1104 in Spring 2012 was 12 – 27. The majority of students in the course were female (67.07%), and 28 students were female among the 37 volunteer participants. For this reason, this case study includes more female students than male students. The range in SLS was considered in order to examine the needs of lower to higher-performing students. The background information for each interview participant is shown in Table 3.2; all names have been changed to pseudonyms to protect the identity of the participants.

Table 3.2.

Participants

Name	Gender	Major	Year of Study in College	TOSLS score
Michael	Male	Psychology	3	12
Emily	Female	Psychology	1	13
Michelle	Female	Public health	3	17
Kate	Female	Pre-business	1	18
Julie	Female	Public health	2	23
Lucy	Female	Psychology	2	25

Data Sources and Data Collection Procedures

Data for this case study were collected through documentation (the TOSLS, the six participants' responses recorded in the *SOLVEIT* database) and semi-structured one-on-one interviews with each of the six participants after they completed *SOLVEIT.* The six participants also responded to an online post-*SOLVEIT* survey about the usability of *SOLVEIT.* Alignment between the research questions and data sources is documented in Table 3.3.

Table 3.3.

Alignment between research questions and data sources

Research questions	Data source
1. How do students use and evaluate *SOLVEIT*?	TOSLS, Documentation (*SOLVEIT* database report), Interview, and Survey
2. What do students perceive as learning gains from completing *SOLVEIT*?	Documentation, Interview and Survey

Data collection procedures are shown in Figure 3.4. Prior to Week One of the study, the instructor taught species concepts, ecological interactions, protists, land plant evolution, and fungi using in-class lectures and activities that included clicker questions, small group and whole-class discussion, and in-class essay questions. In Week One of the study, the participants completed *SOLVEIT* on their own at a time and place of their choosing. None of them asked for help or reported technical issues from us while they were using *SOLVEIT*. The program was available for a three-day period, and students could complete *SOLVEIT* in one or multiple sessions. Students' responses to the prompts, both multiple-choice and constructed-response items, were retrieved from the database to examine how students used *SOLVEIT.*

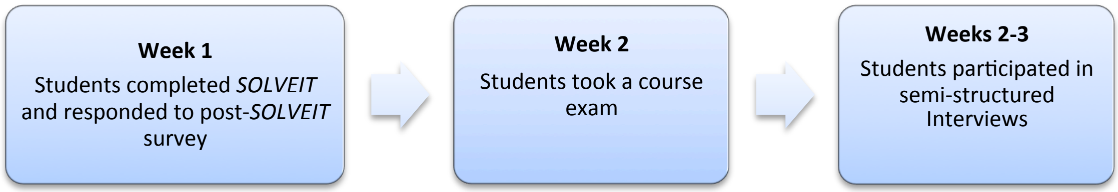

Fig. 3.4. Data Collection Process

After completing *SOLVEIT*, the six participants responded to a Likert-scale survey regarding their perceptions of *SOLVEIT* and the usability of *SOLVEIT* Students were asked to rate a few statements about *SOLVEIT*, ranging from strongly disagree (value=1) to strongly agree (value=5). Items on the survey were as follows:

- I participated in *SOLVEIT* to the best of my ability.
- Overall, I like *SOLVEIT*
- *SOLVEIT* helped me to learn different species concepts and the types of ecological interaction.
- *SOLVEIT* helped me to learn how to solve scientific problems.

In Week Two of the study, following the completion of *SOLVEIT* and the survey, participants took the second of four course exams, which included questions about the material that the instructor taught in class. The exam consisted of calculation, recall, understanding, analysis, synthesis, and inference problems in both multiple-choice and constructed-response formats. During the second and third week of the study, the six students participated in individual semi-structured interviews. They were asked how they used *SOLVEIT* and how the program influenced their problem-solving abilities during the second course exam. During the interview, the interviewer directed them to the *SOLVEIT* website and asked them to comment on what features did or did not work for them (e.g., instructions, tutorials, immediate feedback) and how the program could be improved and modified to better aid their learning and problem solving. All interviews were recorded and transcribed.

Data Analysis

The main goal of this study was to understand and interpret the experiences of the participants who employed *SOLVEIT*. Specifically, the purpose of this study was to determine how the participants used *SOLVEIT*, what they found to be beneficial portions of the program, which parts they felt needed improvement, and how they think the program affected their problem-solving skills. Accordingly, the primary unit of analysis was the six individuals. In this study, we mainly used the constant comparative method of data analysis (Merriam, 2009) to identify themes and patterns related to the *SOLVEIT* experience of the participants. Glaser and Strauss (1967) initially developed the constant comparative method to build grounded theory, but some qualitative researchers (Charmaz, 2002; Merriam, 2009) have argued that the method can be used more flexibly without building a theory.

The systematic approach employed in analyzing the data was conducted as follows. The first author began the process of data analysis by reading iteratively each participant's interview transcription, their documents in the *SOLVEIT* database, and answers from the survey. After reviewing the transcripts, documents, and students' answers more than three times, she started making comments or notations (initial codes) in the margins of data (*open coding,* Merriam, 2009) from a participant and then grouping the initial codes (*analytical coding,* Merriam, 2009).

The researcher next developed a coding scheme and assigned codes to the full data set (see Table 3.4 for an example of the codes used in the analysis). Coding the full data set was iterative. As she assigned codes to data, dozens of categories were generated. The initial set of categories was iteratively revised. Excerpts within each coding category were examined for the purpose of finding recurring themes and patterns. For example, in excerpts in the category "negative/weak features of *SOLVEIT*" the participants clearly present certain features they disliked or ones they found unhelpful, limited, unclear, and etc. Themes and patterns that appeared within each individual participant's experience and evaluation and across different participants' were examined. *MaxQDA* software was used to manage and analyze the collected data. An example of data analysis within *MaxQDA* is shown in Figure 3.5.

Table 3.4
Example of the codes used

Categories	Definition	Codes	Definition	Example
Evaluation on *SOLVEIT* (SI) elements	Elements of SI, which affect positively or negatively the participants' learning and feeling (positive, neutral, or negative/weak)	Positive on step-by-step guidance	Use this code when the participants talk about how they used/felt about positively the guidance of SI	"I probably like the most that it took you step by step." "[SI-guidance] definitely helped me understand how to look at and understand biology problems."
		Positive on immediate feedback	Use this code when the participants talk about how they used/felt about positively the feedback of SI	"You knew right then and there if you are doing it wrong or right. Or, it said 'that's incorrect; this is how you would do it.' Like, it didn't like leave you hanging. It [SI] gave you feedback right away."
		…	…	…
		Negative/weak on constructed-response questions (writing)	Use this code when the participants talk about how they used/felt about negatively writing in SI or what difficulties they experienced in writing in SI.	"Just all of the typing um … that took a long time. The nature of the questions [constructed-response questions] just takes a long time to get through."
		Negative/weak on limited content		"It [SI] only helped me with that one part [argumentation with species concepts] and there was a bunch of things I needed help on."
		…		

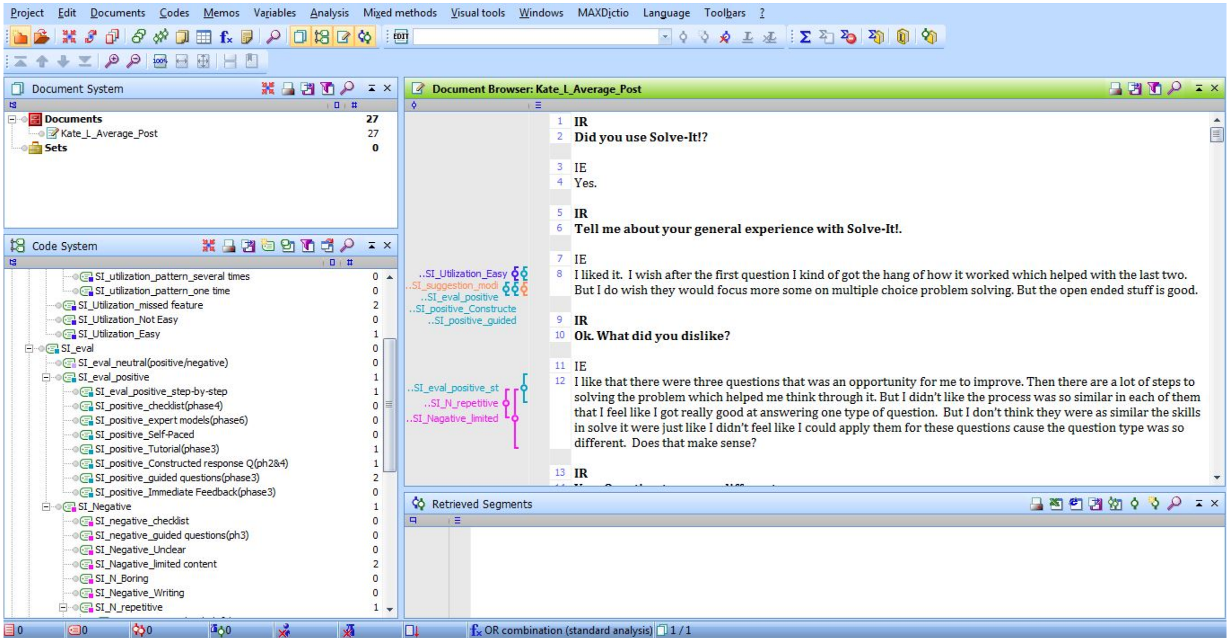

Figure. 3.5. Example of data analysis within *MaxQDA*

Results

Overall, the results from the study indicate that the participants used most features of *SOLVEIT* as intended and they perceived *SOLVEIT* as a useful, effective tutorial program to improve their knowledge and skills for solving biology problems. The findings are presented within the broader categories of the two research questions:

1. How do students use and evaluate *SOLVEIT*?
2. What do students perceive as learning gains from completing *SOLVEIT*?

Research Question 1. How do students use and evaluate *SOLVEIT*?

Three main themes emerged from the analysis related to the first research question: (1) *SOLVEIT* was a convenient, easy-to-use program; (2) the required scaffolds and to a lesser extent the optional scaffolds of *SOLVEIT* helped students solve biology problems; and (3) the procedural and strategic scaffolds of *SOLVEIT* were considered a strong feature of *SOLVEIT*, but the length and limited amount of content were considered weak. Each is described in more detail in the following sub-sections.

***SOLVEIT* was a convenient, easy-to-use program.** All participants had some positive responses to their experience with *SOLVEIT* and perceived it as useful in a variety of ways. The participants liked the idea that they could use the program at their own convenience. All of the participants stated that *SOLVEIT* was easy to use and navigate. As Julie stated:

> It was relatively easy to use. I didn't really have too many problems with it. Like as far as getting on to it and knowing how to navigate it. I think it was a pretty good study tool. …It was really good learning tool. I think it did help.

All six participants expressed a similar sentiment, each reporting that *SOLVEIT* did not present significant problems for use.

***SOLVEIT* helped students solve biology problems.** All participants used the required features of *SOLVEIT* as intended. All six participants responded to the different types of question prompts, which included both multiple-choice and constructed-response formats across all phases.

That said, there were challenges with what the students did with *SOLVEIT*. For example, in Phase 2, the participants were asked to produce an initial answer to each problem that included a claim, evidence, and reasoning. Most of the initial answers were incomplete or flawed. Some provided wrong claims for the problems while some misinterpreted or did not attend to some of the data in the problems. In Phase 4, which follows Phase 3 (engaging in the scientific process), students were prompted to revise their initial answers and provide their final answers. All their final answers included a relatively better quality of reasoning compared to the answers in Phase 2. For example, Michael provided an incomplete answer in Phase 2 of the first problem, but he demonstrated an improved answer in Phase 4. This is shown in the following excerpt from the database report:

> I think at one time they possibly were the same and because of speciation they were able to branch off over time as they spread out over the land. The habitat of each bird seems to have similarities and the overall structure of the birds have little difference. When western and island birds produced hybrids they died out over a period of time. When eastern and western birds produced hybrids only 3 out of 50 made it which seems to indicate that it was not successful. These finding seem to go against the bio species concept which would mean they are each different. (Michael's answer in Phase 2)
>
> I think the Island and Western Jay are different species based on the Bio species concept. This is shown from the graph. When the hybrids were introduced in 2006 they steadily declined until 2010. The Bio Species concept does not apply to the Western and Eastern Jay because there is not enough information or details regarding the hybrids. Based on the first table, western and eastern appear to support the morphological species concept although the island jay is larger. Also the map shows a divide between each species which would mean the birds do not well enough support the ecological species concept since they are not likely to encounter each other. (Michael's answer in Phase 4)

Though all participants demonstrated improvement in their answers, surprisingly, during the interviews, most of them expressed the opinion that the question prompt in Phase 4 (metacognitive scaffolding) was a redundant step, asking the same question, rather than a necessary step to support their reasoning.

In terms of the optional features of *SOLVEIT*, some participants missed or overlooked them. These features are the interactive tutorials (strategic scaffolding in Phase 3), checklist (metacognitive scaffolding in Phase 4), and expert models (strategic and metacognitive scaffolding in Phase 6). The interactive tutorials are activated whenever wrong answers to certain questions are given. Although most participants perceived the interactive tutorials to be useful, they provided two reasons for skipping them. Some stated they had disregarded the interactive tutorials because they already knew the information there; others said the interactive tutorials were too time-consuming because they included multiple pages. However, Kate actually used the tutorials when they were activated, and she was positive about one of them:

> The assumptions one [One of the tutorials]. That was really helpful because I'm not good at that. Or, that's one of my weak points. I think that one actually came up in the middle of one of the problems. That was helpful, cause I haven't really ever seen a tutorial on that. So, having the different steps and going through them and, then, the practice questions. Not the practice question, but the scroll over, and you could see the answer kind of thing. That helped, cause it was like a fast way to just kind of like go through it; like, it wasn't like quizzing.

There were three students who skipped the checklist. Julie mentioned that she already knew all the information regarding building a scientific solution offered in the checklist and thus considered it unnecessary. Only two of the six students agreed that the checklist was helpful for revising their initial solutions.

Surprisingly, only two out of six participants used the expert models. The other four participants missed the feature, because they did not recognize that there was a review session including the expert models. Michelle, one of the participants who used the expert models, indicated that they were helpful:

> Actually the answers [the experts' models] helped me more than actually answering the actual question. Cause if I can look at the answer first and then go back and answer a different question I can construct a better answer.

In sum, all six participants used the required features of *SOLVEIT*; some (n=) showed constructive and active use of the required features; the others showed superficial use. Participants demonstrated different patterns in using optional features of *SOLVEIT.* Some focused more on completing *SOLVEIT* rather than spending time to use the optional features; the others used those features as additional support to help their problem solving.

Strong and Weak Features of *SOLVEIT.* All the participants indicated that the step-by-step guidance with the immediate feedback feature in Phase 3 (strategic and procedural scaffolding) as the greatest advantage of the program. As an example, in Phase 3, students who answer incorrectly receive immediate and explanatory feedback. Michelle stated:

> I probably like the most that it took you step by step. Like once you answered, put in an answer, and it popped up. It's like 'you got it'.... So, you knew right then and there if you are doing it wrong or right. Or, it said 'that's incorrect; this is how you would do it.' Like, it didn't like leave you hanging. It gave you feedback right away.

Higher-performing students (Julie and Lucy, based on the TOSLS scores) provided both positive and negative evaluations on the step-by-step guidance and used those scaffolds in a different manner from the lower-achieving students. Julie said she expected a quick review rather than the step-by-step guidance, and she answered the questions in the steps to confirm what she already knew.

Students reported several troublesome features of *SOLVEIT* as well. For example, almost all the students (n=6) thought *SOLVEIT* was repetitive, even though they admitted that repeating the same phases (Phase 1 through Phase 6) within the three different problems helped them learn by reinforcing the material. Lucy said the third iteration that provides a third problem with the similar scaffolds was unnecessary:

> It did get a little monotonous, though. A little like doing the same things over and over, which I mean, repetitions helps you learn, but, so, I can see why it would be that way… I think two questions would have been sufficient for me at least. Some people may need the third repetition. But I thought I understood it well after two questions.

Emily had positive views of *SOLVEIT*, but she was frustrated because what she wanted most was the answer to the question. But to find the answer, she had to go through a long process and she could not skip the phases:

> My experience is I thought it was good. I mean, it gave me good information but it… felt like I was doing the same thing over and over again and it took a really long time to get the information [the answer] that I needed, which I found stressful.

Four participants reported the length as a disadvantage of *SOLVEIT.* Specifically, they pointed out that that constructed-response question prompts (in Phase 2 and 4) require a lot of writing and time. Julie said:

> It was a little long. It was just very long, which if you're … you know, pressed for time, you only have a short amount of time to do it, or if you just try to do a little bit of a review before class, then it's not so great for that type of thing. Well, the questions are long and… multiple-choice questions… there were a lot of those. It took a while. Also, just all of the typing um … that took a long time. The nature of the questions [constructed-response questions] just takes a long time to get through.

Four out of six participants (lower- and intermediate-performing students) pointed out that limited amount of content (i.e., only focusing on species concepts and ecological interactions) and a small number of problems were drawbacks of *SOLVEIT.* They said they expected *SOLVEIT* to be a program that covered more concepts and a larger variety of problem types. Emily said:

> If it was an actual review of the test instead of just one thing [a type of problem]… Cause I thought it was going to help me for the test, but it only helped me with that one part and there was a bunch of things I needed help on.

In sum, all six participants expressed a similar sentiment, each reporting that *SOLVEIT* has positive aspects, such as immediate feedback, as well as inconvenient and unfavorable ones, such as a long process in different phases.

Research Question 2. What do students perceive as learning gains from completing *SOLVEIT*?

Two main themes emerged from the analysis related to the second research question: (1) *SOLVEIT* was helpful to correct students' misconceptions about species concepts and apply those concepts appropriately to the problems, and (2) students reported they were able to employ a wide range of problem-solving skills as they solved problems with *SOLVEIT*. Each is described in more detail in the following sub-sections.

Conceptual Understanding. All of the participants agreed that *SOLVEIT* helped their understanding of species concepts and ecological interactions. Michael said, "*SOLVEIT* helped that [learning concepts] for sure, because you learn the definition over an over again and how to apply it." Consistent with the findings from the interviews, documentation analysis showed that students' definitions and understanding improved as they went through *SOLVEIT*. For example, before using *SOLVEIT* scaffolds, Emily defined a species concept as follows, "One species concept is biological evolution about how they evolved over time." As illustrated below, Emily gave a more in-depth and organized answer employing improved conceptual understanding in her revision:

> The Western and Easter toads may have one time been the same species. They probably share the same common ancestor. [No data supported] From Table 2, we see that the western and eastern toad made offspring. However we see from Figure 2 that the population of the hybrid toads went to 0, which could lead someone to make the inference that the toads are not the same species. (Emily's pre-answer on Problem 2)
>
> According to the morphological and ecological concept and Figure 1, the eastern, western and island toads share similar qualities. However, after looking at Figure 2 and Table 2, the biological species concept would support that they are not the same species, because their offspring was either infertile, and was also not viable because it was all depopulated after just 4 years. (Emily's post-answer on Problem 2 after using *SOLVEIT* scaffolds)

All six participants expressed similar opinions, each reporting that *SOLVEIT* was helpful for improving their conceptual knowledge.

Problem-Solving Skills. Four participants responded that *SOLVEIT* helped their learning of how to solve scientific problems. Lucy said:

> Like tying your reasoning back to the facts that you used. Also, just to be more aware of what the questions were asking specifically. (…) I think the multiple choice questions in *SOLVEIT* [strategic and procedural scaffolding in Phase 3] helped for me to individually interpret each piece of data then I could get the overall picture.

Michelle said, "[*SOLVEIT*] definitely helped me understand how to look at and understand biology problems." She gave a detailed account of her learning gains in problem solving:

> I think just how to look at problems step by step definitely. I feel like I've said that a lot but definitely had not to just jump into it and not really think about a method you have to have a method to answer the questions. Because before I was just kind of like, "What are they asking me for?" and didn't have a logical way of working through the problem. And this [*SOLVEIT*] gave you a logical way of arriving at an answer with everything covered.

Julie said she had learned about how to analyze multiple data in tables and graphs. She stated:

> How two different types of data are related and um, what background knowledge you have can be applied to different data. So, it [*SOLVEIT*] helps, you know, the understanding tables and graphs and reading graphs. I'm a Psych major so we do a lot of reading graphs and stats and stuff like that. So, I think it helps with that class too even though the information was about biology I was able to use um, understanding graphs and tables in my Psych class.

Four participants reported that their abilities to build scientific solutions were enhanced by using *SOLVEIT.* Lucy said, "I think I learned comparing and contrasting data and figuring out which piece of data best represents argument I'm trying to make." Michael said:

> *SOLVEIT* helped with that [building solutions] because you've gotta pull stuff from charts and tables and graphs and put it into your answer because that's one of the ways you're going to defend your answer is by showing proof from different statistics and figures and stuff.

In sum, all six participants said that *SOLVEIT* benefited their learning in some ways, each reporting that they employed effective problem-solving processes through completing *SOLVEIT*.

Conclusion and Discussion

The findings of this initial evaluation study demonstrate that *SOLVEIT* has the potential to improve students' conceptual understanding and problem-solving skills in biology. Our data suggest components of *SOLVEIT* that should be retained or revised; in particular, we should make refinements to the scaffolding strategies in *SOLVEIT*. Our findings are consistent with the literature on computer-based scaffolding of problem solving and expand the understanding of designing an effective scaffolding approach. In this section, overall implications about the design of computer-based scaffolding are discussed, as well as suggestions for future research.

The procedural and strategic scaffolding (Phase 3) that guides a student through the process of approaching the problem was *SOLVEIT*'s best feature, according to student users. Similarly, in the study of Oliver and Hannafin (2000), procedural scaffolds were shown to effectively regulate middle school students' problem-solving processes in science. Another study (Shen, 2012) also demonstrates the effectiveness of procedural scaffolds on the improvement of college students' reasoning in an introductory instructional technology course. In this current study, students also reported that the strategic scaffolding in *SOLVEIT* via question prompts and immediate feedback helped them to identify *how* to deliberately approach the problem and to determine *why* the chosen answer was right or wrong. The strategic scaffolding helped students gain competency in solving problems. We intend to retain this feature in *SOLVEIT*. Another strategic scaffolding, the interactive tutorials in Phase 3 that were suggested but optional, were employed less effectively. Thus, we need to revise the instructions to emphasize more clearly the benefits; in that way, students may value the optional feature more. Also, the contents of the tutorials should be presented more succinctly because some students reported that they had too many pages and were too time-consuming.

The length of *SOLVEIT* with different kinds of scaffolds in Phase 1 through Phase 6 should be revised. In the current version all students have to go through all the phases regardless of their needs or their levels of expertise. We designed *SOLVEIT* in this way as a first attempt to test the idea of a problem-solving tutorial program for introductory biology. But, others have suggested that computer-based scaffolding that lacks flexibility for users is not ideal (Saye & Brush, 2002). According to Oliver and Hannafin (2000), young students (8th grade students in their study) tended to avoid using irrelevant scaffolds to their needs. Similarly, in this current study, some students did not like the constraint of having to complete all the six phases in *SOLVEIT*. We may argue, regardless of age (e.g., K-12 vs. college students), irrelevant scaffolds may lower students' motivation and negatively impact their problem-solving momentum. We suspect that the higher-performing students already had adequate knowledge and skills to solve the problems in an efficient way before attempting *SOLVEIT,* and they did not need as much scaffolding as *SOLVEIT* provided. They might be able to complete those problems unaided, and the scaffolds might increase their cognitive load. This suggests that the computer-based scaffolding approach may not compel high-performing students to strictly follow a pre-defined problem-solving path. Instead, it might be more beneficial to allow them to follow their own problem-solving plan with supportive guidance illustrating the desirable problem-solving process. Otherwise, computer-based scaffolding would provide high-performing students the flexibility to select the amount of and types of scaffolds.

However, we hypothesize that this compulsory, phase-by-phase practice with various types of scaffolding can be useful for average- and low-performing students in helping them to understand the scientific problem-solving process. In our study, average- and low-performing students objected to this feature of *SOLVEIT*, but we suspect that these students can greatly benefit from the different scaffolds in the pre-defined phases. The provided scaffolds controlled their problem-solving processes in some ways, but they practiced necessary problem-solving processes (e.g., evaluating their answers) during a series of problem-solving activities, and as a result, they achieved improved problem-solving skills by taking the suggested learning path. Students can internalize problem-solving processes through repeated structured practice (Puntambekar & Hübscher, 2005). The scaffolds may also help them to be more reflective by shifting their focus from finding or generating a solution to understanding of the necessary skills in problem solving.

Computer-based scaffolds are not as flexible and responsive to students' needs as human tutors or advanced peers. Thus, different computer-based scaffolds should be designed for high- and low-achieving students. To maximize the benefit of *SOLVEIT* for different levels of students, we intend to create different versions of *SOLVEIT* that can be used by students at different levels.

The results of this study also indicate that though students utilized the required metacognitive scaffolding in *SOLVEIT* as intended, which encouraged them to reflect upon their answers and cognitive processes, only a few participants appreciated that feature and took their reflection activities seriously. Most of the participants pointed out that the feature was unnecessary and required a lot of time. In addition, most participants skipped over the optional metacognitive scaffolding (experts' models). Previous research studies conducted in K-12 contexts reported many young students do not know how to use metacognitive skills and tend not to use computer-supported metacognitive scaffolds (Davis & Linn, 2000). Similarly, many college students may not be ready to employ metacognitive skills or simply ignore metacognitive scaffolds, because they cannot see immediate benefit for their learning. In addition, metacognitive activities may increase cognitive load, which is challenging for lower-performing students who tend to seek correct answers rather than reflect upon the entire problem-solving process.

Typically, in large-enrollment science classrooms, teachers and their teaching assistants are not available to provide metacognitive scaffolding for their students. This is a serious concern. Two solutions should be pursued. First, administrators should recognize that large-enrollment courses need more human resources so that problem solving and metacognition can be taught. Second, researchers should consider the positive potential of computer-based metacognitive scaffolding in a problem-solving context, but should make an effort to design computer-based metacognitive scaffolds that do not significantly increase cognitive load (Gama, 2004). It would be beneficial to design a separate, preparatory session to teach what metacognition is, emphasize the importance of metacognition, and encourage students to practice metacognitive strategies as well as to embed immediate metacognitive prompts, support, or feedback during problem solving (Roll, McLaren, & Koedinger*,* 2007).

The overall results of this study indicate that the scaffolding strategies in *SOLVEIT* helped to increase students' learning gains in content knowledge, scientific data analysis, and reasoning. However, it should be noted that the study is subject to certain limitations. The study included a small number of participants. Hence, the sample from which the data are reported may not be representative. A larger subsample may provide more varied and comprehensive understanding about which features of *SOLVEIT* work or do not work. There was not a way to track student use of *SOLVEIT* in real-time. This is a limitation of the program and is being considered as a potential addition to future versions.

This current qualitative case study provides some evidence of the ability of *SOLVEIT* to facilitate the development of students' problem-solving skills. However, more research is needed and the findings should be considered preliminary evidence that demonstrates the potential of *SOLVEIT*. In addition, in this paper, we only present one study related to how *SOLVEIT* works with students at different levels of performance. We have conducted larger-scale research studies on *SOLVEIT*'s impact on students' problem-solving skills and further investigations through qualitative case studies to determine if students with different levels of learning performance learn different skills through using *SOLVEIT*. The findings from these studies will be reported in other appropriate journals.

There are also several areas to be considered for future research. First, previous research indicates that students can enhance their problem-solving skills through argumentation activities (Stegmann et al., 2012). Data from this study indicates building arguments in *SOLVEIT* may enhance students' problem solving capacities. The potential of argumentation activities to improve problem-solving skills is a growing area of research and additional examination of the relation between problem-solving and argumentation skills is needed. Second, *SOLVEIT* encompasses various types of scaffolding to help students' problem-solving processes. But, this study did not provide sufficient evidence of how *SOLVEIT* enables students to build their sound arguments and fully explain what features of *SOLVEIT* actually influence students' problem-solving performance. More research is needed to explore how each scaffolding mechanism of *SOLVEIT* assists students' argumentation as well as problem solving. Further study is needed to examine the interplay and interaction between different types and mechanisms of scaffolding to create a synergistic effect among the scaffolds provided in *SOLVEIT*.

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CHAPTER 4

THE IMPACT OF COMPUTER-BASED SCAFFOLDS ON COLLEGE STUDENTS' DOMAIN KNOWELDGE AND PROBLEM-SOLVING SKILLS IN AN INTRODUCTORY BIOLOGY COURSE[3]

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Abstract

Solving complex problems in introductory biology courses is challenging for college students because it requires well-integrated knowledge and skills. Many of these students will not continue with biology as their chosen major and, consequently, do not see the value in developing these skills. The researchers have designed and implemented a self-directed, Web-based tutorial program, *SOLVEIT*, to support the development of college students' knowledge and skills to solve complex biology problems. The focus is placed on developing knowledge and skills based on the assumption that students who actually perform problem-solving skills better will choose to pursue further study in biology and the sciences, in general. This program provides students with problems within the biological domains of evolution and ecology, takes them through the scientific problem-solving process to draw a conclusion, and provides scaffolds (e.g., prompts, interactive tutorials, and expert models) while solving the problems. This mixed-method study investigated the impact of *SOLVEIT* on college students' problem-solving skills. Data sources included pre- and post-test scores and semi-structured interviews. The results demonstrate the effects of *SOLVEIT* for enhancing conceptual understanding and problem-solving processes in the context of these topics in an introductory biology course.

Introduction

Over the past few decades, studies on the differences between problem solving of experts and novices have received significant attention in the science education literature (Bodner, 1991; Camacho & Good, 1989; Nehm & Ridgway, 2011; Sumfleth, 1988). There is a comprehensive body of empirical findings that suggest experts and novices’ problem-solving performances are distinguished in respect of cognitive strategies for problem solving (Camacho & Good, 1989; Chi, Feltovich, & Glaser, 1981; Heyworth, 1999; Nehm, 2010; Smith, 1988; Smith & Good, 1984). Experts possess a deep understanding of the content domain, and the domain knowledge is well organized (Reif, 2008). Experts also tend to solve science problems in a more organized manner using more procedural knowledge than novices (Priest & Lindsay, 1992; Woods, 1989). Unlike experts, novices present inadequate content knowledge or surface level conceptual understanding, tend to build their solutions based on the analysis of pieces of information, and are not aware of their strengths and weaknesses in solving problems (Larkin et al., 1980; Priest & Lindsay, 1992). In a study on genetics, Smith (1988) found that novices' problem solving approaches to complex problems are very simple or poorly organized. Therefore, a prominent goal of college science education should be to foster those cognitive abilities that enable more effective problem solving.

Scaffolding from teachers is needed to help students improve problem solving, but providing scaffolding is challenging given limited resources. Previous research studies suggest that acquiring thinking skills in science can be achieved or accelerated through *scaffolded instruction* (Eslinger, White, Frederiksen, & Brobst, 2008; National Research Council [NRC], 2012). Scaffolding is specific and targeted support for learners provided in addition to primary instruction aimed at helping learners develop competence and confidence. Traditionally, a teacher or a more capable peer provides scaffolding to help a learner achieve a learning goal or accomplish a task in the learning process (Vygotsky, 1978). Teachers are expected to provide the right amount of support and an appropriate type of guidance to each student based on that student's progress and needs. Unfortunately, due to a number of barriers, including limited classroom time, inadequate resources (technology, tools, etc.), and a lack of people resources, it is difficult for teachers to effectively support students' problem-solving processes in large classes or even in small classes where there may be a wide divergence of individual needs and problems.

In recent years, researchers have suggested design guidelines for developing effective computer-based scaffolding in teaching critical cognitive skills (e.g., Saye & Brush, 2002; Sharma & Hannafin, 2007). Computer-based scaffolding has been shown to enrich science instruction in K-12 contexts (Linn, 2005; Scardamalia & Bereiter, 1991; Songer, 2006). However, only a few of these research studies have focused on computer-based scaffolding for college students in science education. Though it seems impossible for computer-based scaffolding to provide the highly dynamic scaffolds of one-on-one instruction from a teacher, research focusing on how to design more effective computer-based scaffolding to facilitate students' problem solving in large college science classes in which the teacher's attention is not available may provide useful insights into how to get closer to the one-on-one experience.

In the present study, the researchers designed a Web-based self-directed program, *SOLVEIT* grounded in a scaffolding framework (Kim & Spector, in preparation). *SOLVEIT* was designed to support the development of college students' problem-solving skills within the biological domains of evolution and ecology. *SOLVEIT* were built using *PHP* and *MySQL* and can be accessed at http://solveit.uga.edu. In *SOLVEIT*, students engage in solving three biology problems with various scaffolds, which require use of data to draw sound conclusions based on species concepts and ecological interaction with the following problem-solving processes: (a) constructing a solution to each problem without guidance, (b) answering a series of multiple-choice questions about the process of solving each problem: clarifying the problem, analyzing scientific data, examining possible assumptions and drawing a conclusion, (c) revising the initial solution, (d) explaining the problem-solving strategies needed for each problem, and (e) reflecting on their answers and the expert's responses.

Methods

The purpose of this research study was to examine the effects of *SOLVEIT* on students' problem-solving skills. This study employed mixed methodology (Creswell & Plano Clark, 2007), including a two-group pre-test and post-test design (experimental and comparison group) and qualitative case study (Stake, 2000). Students in the experimental group solved the three biology problems with scaffolds in *SOLVEIT*. Students in the comparison group solved the same three problems in a Web-based site without scaffolds (also designed and developed by the authors) and then received correct answers developed by the course instructor (the second author) in the site. This study aimed to answer the following question: How does *SOLVEIT* affect the development of the problem-solving skills of undergraduates enrolled in a non-majors introductory biology course?

Context and Participants

The setting for this study was an introductory biology course (Organismal Biology) in the division of biological sciences at a large public university in the Southeastern United States. The course introduces students to the concepts, principles, and theories of biological science and teaches problem-solving skills required to solve biology problems – e.g., species concepts, organism interactions, protists, plant/animal evolution, bacteria, and fungi. Students who typically take the *Organismal Biology* course are non-science major students who are at differing grade levels (freshmen through seniors).

Data was collected from two sections of the course taught by the same instructors. The total number of students enrolled in two sections of the course during fall semester in which data was collected was 319. Of the 319 students, 184 students volunteered to participate in this study. The participants were ranked from the highest to lowest scores according to their levels of scientific literacy skills (SLS) as measured by the Test of Scientific Literacy Skills (TOSLS) (Gormally, Brickman, & Lutz, 2012) that was administered in class in the beginning of the course. TOSLS is a validated measurement tool to assess college students' scientific literacy skills in biology. The TOSLS has a maximum possible score of 28. The range of scores among the participants was 8 – 28. After establishing the range of scores, zero and one were assigned to a list of ranked participants (e.g., 8 = 0; 9 = 1; 12 = 0; 15 = 1). Students assigned the number zero were in the experimental group; the students assigned the number one were in the comparison group (initially, 92 students were in each group). Using this method, the researchers could ensure that the same number of below-average, average, and above-average SLS students were in both groups.

149 of the 184 (70 students in the experimental group and 79 students in the comparison group) completed the three biology problems either in *SOLVEIT* or in the Web-based site without scaffolds. Of the remaining 149 participants, 45 students (17%) were male, and 104 students (83%) were female. Most of the students were sophomores or juniors. Table 4.1 presents the two groups' scores on the TOSLS, and results indicate that the two groups were homogenous based on the TOSLS score (P=.917).

Table 4.1.

TOSLS scores of the experimental and comparison groups

Group	n	TOSLS mean	TOSLS SD
Experimental	70	20.04	1.121
Comparison	79	19.51	1.092

Initially, the researchers contacted 32 of the 70 students of the experiment group (10 above average SLS students, 10 average SLS students, and 12 below average according to the pre-TOSLS scores) for pre- and post-semi-structured interviews. Critical case sampling (Patton, 2002) was used to ensure that the subsample reflected the demographics of the course in terms of gender and TOSLS scores. Twenty of the 32 students responded to the interview requests, and finally, sixteen students participated in the pre- and post-interviews. Of the 16 participants, 4 were low performing (below average SLS, scores between 12-17), 6 were intermediate performing (average SLS, 18-22) and 6 were high performing (above average SLS, 23-26). For the purpose of this study, the researchers did an in-depth analysis of the data from 50% of the total number of the participants (8 students). The eight interview participants were divided into two primary categories labeled “low-performing” or “high-performing.” Participants were placed in each category on the basis of their TOSLS scores. Table 4.2 presents a summary of participants’ biographical and background information (names in this table and subsequent references to the participants are pseudonyms to preserve anonymity).

Table 4.2.

Profiles of the participants

Category	Name	Gender	Year	TOSLS
Low-performing	Shelly	Female	2	12
(Below-average	Olivia	Female	2	15
SLS)	Monica	Female	2	15
	Bella	Female	1	17
High-performing	Serena	Female	2	24
(Above-average	Blair	Female	2	24
SLS)	Jessica	Female	4	26
	Ethan	Male	2	26

Data Collection Procedures and Methods

Data were collected throughout the Fall 2012 semester. Figure 4.2 shows our data collection procedures.

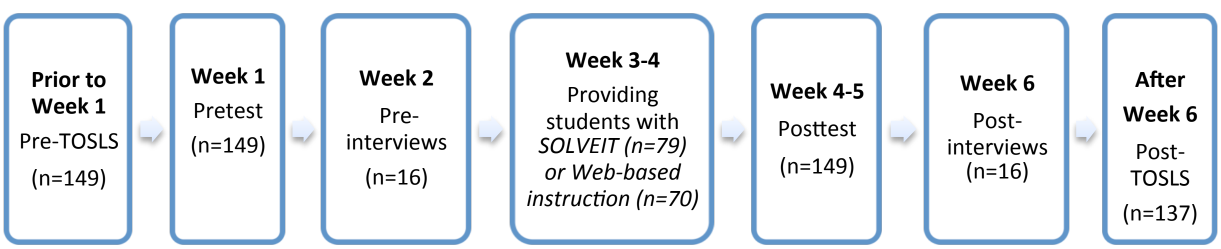

Figure 4.1. Data collection procedures

All participants took the TOSLS in the beginning of the course under the administration of the course instructor in class. Scores from the TOSLS were subsequently used for the purposes of grouping (experimental and comparison) and sampling (a small number of the participants for the qualitative case study). They took the same TOSLS again at the end of the course. For five weeks prior to Week One of the study, the instructor covered the following topics: species concepts, ecological interactions, protists, land plant evolution, and fungi using in-class lectures and activities that included clicker questions, small group and whole-class discussion, as well as in-class essay questions.

In Week One of the study, the 149 participants took a pre-test. After the pre-test, in Week Two of the study, pre-interviews were conducted with the selected four participants before they completed *SOLVEIT.* During the pre-interviews, the participants were asked to solve biology problems. Then, the 149 participants were asked to solve three biology problems in either *SOLVEIT* or the Web-based site without scaffolds over a period of 10-days. Students could access *SOLVEIT* anytime they were available during the 10-day period. A few minor technical difficulties (e.g., inability to login) were reported and were resolved by the authors. In Weeks Four-Five of the study, following the completion of *SOLVEIT,* the students took the post-test. Students learned about bacteria, archaea, and protists in class before the post-test. In Week Six of the study, during the post-interviews, the four participants were asked to solve similar biology problems.

Test of Scientific Literacy Skills (TOSLS). Students' scientific literacy skills (SLS) were measured by the Test of Scientific Literacy Skills (TOSLS) (Gormally, Brickman, & Lutz, 2012) at the beginning and end of the course. The TOSLS has 28 questions and a maximum possible score of 28. TOSLS is a validated measurement tool to assess college students' scientific literacy skills in biology consisting of "recognizing and analyzing the use of methods of inquiry that lead to scientific knowledge and the ability to organize, analyze, and interpret quantitative data and scientific information" (Gormally et al., 2012, p.364). This tool has been used in other contexts exploring students' scientific literacy skills in post-secondary biology courses.

Pretest and posttest. Students in both groups took Course exams 1 and 2 and each course exam included 31 multiple-choice questions on a 3-point scale and one constructed-response question on a 7-point scale. The constructed-response question related to species concepts on Exam 1 was used as a pretest to assess students' problem-solving skills before using *SOLVEIT*. The constructed-response question related to species concepts on Exam 2 was used as a posttest assessment after using *SOLVEIT*. There was a total of 7 points possible on the pretest and 7 on the posttest. It should be noted that although the data set and species (e.g., snakes for the pre-test and bacteria for the post-test) differed in the pre-test, the post-test, and *SOLVEIT*, they were all alike in terms of their level of difficulty and structures – all of the questions were created by the experienced course instructor (the fourth author) (see Appendix A). With only surface-level differences, the questions all asked students to draw a conclusion based on analysis of multiple data.

Semi-structured interviews. The researchers conducted semi-structured interviews to examine differences in the participants' levels of domain knowledge and problem-solving skills before and after *SOLVEIT*. During the interviews, the participants were asked to solve problems while being audiotaped. The interviews were conducted two times for each student, before and after students used *SOLVEIT.* For the pre- and post-interviews, we used four biology problems relevant to species concepts content (see Appendix A). All of the problems used in the interviews asked whether the provided species in a problem were the same species or not. The four biology problems for the pre-interview include two questions from Exam 1, whereas the four biology problems for the post-interview included two questions from Exam 2. Two problems (one multiple-choice and one constructed-response question) were the same in the pre-and post-interviews.

During both the pre- and post-interview sessions, all students were given the same conceptual question regarding species concepts: What are the species concepts? How do you define the concepts? Then, we provided the biology problems one by one and waited until the students found correct answers for the problems and were ready to answer our interview questions as follows: (1) What is the problem asking? (2) What is your answer? (3) Can you describe the steps used to arrive at your answer? (4) Did you have any difficulties with this problem? (5) How did you use each piece of data to answer the problem? The participants were encouraged to elaborate their processes of problem solving, as they were involved in each problem so as to uncover how each interviewee was thinking about and then solving the problem.

Data Analysis

In this section, we describe both statistical analysis using a repeated measure analysis of variance (ANOVA) and qualitative analysis using constant comparison methods.

Statistical Analysis. The 149 written constructed-responses from the participants' pre-tests and post-tests were analyzed. Students' responses include three parts: a claim, evidence, and reasoning to justify the claim. We developed a score rubric based on the argument model developed by Tulman, Rieke and Janik (1984), which assigns scores to the three different dimensions, "claims" (0-1 points), "evidence" (0-3 points), and "reasoning" (0-3 points) (See Appendix B). The claim dimension involves reaching (or not reaching) an accurate conclusion. The evidence dimension involves (correct or incorrect) interpretation of appropriate evidence.

The reasoning dimension involves the extent to which the student is synthesizing evidence, linking the claim and the evidence by employing the appropriate scientific principles, and articulating why they believe the evidence supports the claim. Three raters, the first author (HSK), the second author (PPL, the instructor and *SOLVEIT* project PI), and a graduate assistant majoring in plant biology, independently applied the rubric to a random selection of 12 responses and then compared scores. The percentage of the initial agreement on the scores between the raters (inter-rater reliability) was 54%. We further discussed scoring and independently scored more responses until we reached 100% agreement on the scores (total 18 responses). After 100% agreement on scoring was achieved, one of the authors scored the rest of the responses. A total numerical score was calculated for each participant. We used repeated measure ANOVA to compare mean scores from the pre-test and post-test in the experimental versus comparison groups. In addition, the participants' pre- and post-TOSLS were analyzed. We used repeated measure ANOVA to compare mean scores from the pre- and post-TOSLS in the experimental versus comparison groups.

Qualitative Analysis. The unit of analysis for the case study was the individual student. Audio-recorded interviews were transcribed for in-depth analysis. The researchers focused on both the similarities and differences in problem-solving performance among the eight participants, as well as between the pre-interviews and post-interviews. The first author (HSK) used open coding and the constant comparison method based on grounded theory to analyze the participants' problem-solving performance (Glaser & Strauss, 1967). The overall data analysis procedure was completed in six steps. Details for each step are outlined in Figure 4.3.

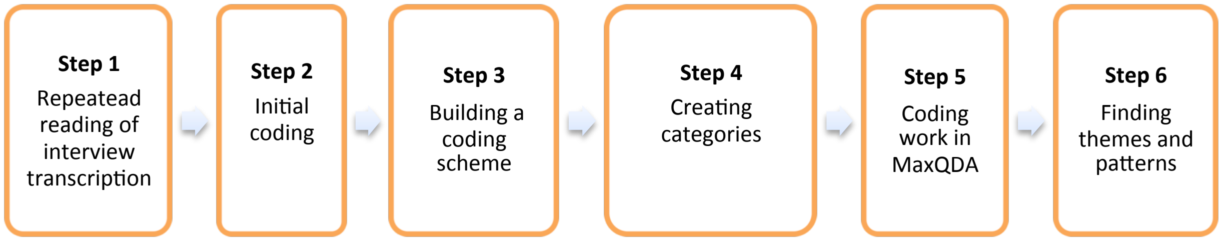

Figure 4.2. Qualitative data analysis procedure

First, HSK repeatedly read through all interview transcripts, which describe how students solved biology problems relevant to species concepts content, over several weeks. HSK made notes about the participants' knowledge and skills (e.g., accurate conceptual understanding or misconceptions and desirable or low-level problem solving approaches). Second, HSK classified and grouped the notes into relevant categories: conceptual understanding, reasoning, use of data, metacognitive strategies (e.g., checking) – "initial coding." Third, based on initial coding work, HSK built a coding scheme by identifying categories and sub-categories. New codes were created where appropriate while building the coding scheme (see Table 4.3). For example, in the pre-interviews, students often used words like "I guess" to depict their problem-solving steps, so we formed a category to describe this and called it the "unsuccessful problem-solving behavior." In contrast, in the post-interviews, students used more words like "asked, compared, and concluded" to depict their problem-solving steps, so a category was formed to describe this called "successful problem-solving behavior." Fourth, the categories and sub-categories were organized into four overarching categories: conceptual understanding, use and interpretation of data, and problem-solving processes. Fifth, the coding scheme was applied to all transcripts using *MaxQDA*, a qualitative data analysis software package. Finally, common emergent themes and patterns for each category were generated within the same participant and across different participants.

Table 4.3.

Codes for problem-solving behaviors

	Code	Description
Successful	Analyzing BSC	Interprets data in graphs and tables correctly
	Analyzing MSC	Interprets data in figures and tables correctly
	Analyzing ESC	Interprets data in figures and tables correctly
	Synthesizing	Synthesizes data analysis (makes logical connections among the different evidence of the problem) (e.g., weighing data)
	Evaluating and monitoring	Reviews problem-solving processes and fixes their mistakes themselves during the problem-solving process, which leads to the correct solution/answer
	Application of procedural knowledge	Uses appropriate procedural knowledge needed for the problem during the problem-solving process *This code is applied only once for each problem.

	Code	Description
Unsuccessful	Overlooking evidence	Overlooks evidence that is provided in the question, often stating that there is no evidence Solves a problem using partial data analysis (disregards evidence w/o intent)
	Disregarding evidence	Not using the data with intent, did look at it maybe
	Misinterpreting BSC	Incorrectly interprets BSC data in graphs and tables
	Misinterpreting MSC	Incorrectly interprets MSC data in figures and tables
	Misinterpreting ESC	Incorrectly interprets ESC data in figures and tables
	Incomplete analysis BSC, MSC, ESC	This code is applied when the student doesn't use all of the data a piece of evidence provides. This is similar to misinterpretation except that they do analyze the data correctly just not completely Breakdown by species concept and, then, by format of data
	Guessing strategies	Use of guessing strategies, not followed up by evidence
	No/Inconsistent Monitoring/evaluation	Changes answers during the problem-solving process (contradicting self, multiple answers), which leads to an incorrect solution/answer
	Within data distractor	Becomes distracted by minor/superfluous data (Overly used/analyzed minor data)

	Beyond data distractor	Creates assumption about the data, predicts what they think it might mean and, then, gets distracted by their predictions (Non data-based analysis)
	Lack of procedural knowledge	Describes disorganized problem-solving process *This code is applied only once for each problem.

Results

The results indicated that overall, *SOLVEIT* participants increased their scores in the posttest compared to the pretest. Prior to *SOLVEIT*, most students formulated unsophisticated solutions to the pretest items; following *SOLVEIT*, a meaningful improvement was found in students' written argumentation abilities. Also, students' problem-solving processes improved significantly after completing *SOLVEIT* with respect to use of major biological concepts, reasoning with provided data, and an organized problem-solving approach.

How does SOLVEIT affect the development of the problem-solving skills of undergraduates enrolled in a non-majors introductory biology course?

Quantitative Findings

To assess the effect of *SOLVEIT* on students' problem-solving skills, students were asked to take a pretest and posttest that were relevant to species concepts content and required argumentation abilities. We found a significant increase in the experimental group scores on the posttest. Namely, the results indicate that students' problem-solving skills were significantly affected by *SOLVEIT* (M = 6.01, SD = .940 and M = 5.44, SD = 1.035, respectively; $F(1,148)=4.061$, $p < .05$). The data from the pre- and posttest are presented in Table 4.3. The difference between the two groups was statistically significant with a small Effect Size (ES). This result provides evidence that students advanced their problem-solving skills following the implementation of *SOLVEIT.* On the other hand, there was no significant difference between the experimental and comparison TOSLS scores. $F(1,136)=0.048$, $p=.827$

Table 4.4

Pretest- and posttest-scores of the constructed-response items

	N	Pretest score		Posttest score		ANOVA		
Group		M	SD	M	SD	F(1, 148)	*p*	ES
Experimental	70	5.47	1.032	6.01	.940	4.061	.046	.027
Comparison	79	5.30	1.148	5.44	1.035			

Qualitative Findings

The results of the qualitative analysis demonstrated the efficacy of *SOLVEIT* for improving both low- and high-performing students' domain knowledge and problem-solving skills in biology. The eight participants employed more successful problem-solving strategies and fewer unsuccessful problem-solving strategies during the post-interviews, after using *SOLVEIT,* than the pre-interviews (see Table 2 for the list of successful and unsuccessful problem-solving behaviors/strategies).

All of the four low-performing participants (below average SLS students) demonstrated significant improvement in recalling and defining species concepts and in problem-solving skills after *SOLVEIT*: Shelly (TOSLS score, 12), Monica (15), Olivia (15), and Bella (17). Bella showed the least improvement among the four students. High-performing students (above average SLS students) showed moderate levels of domain knowledge and problem-solving skills before *SOLVEIT* and demonstrated improvement in those areas: Blair (24), Serena (24), Jessica (26), and Ethan (26). Specifically, the participants demonstrated improvement in problem-solving skills in the following areas: (a) use and interpretation of data grounded in the domain of evolution and (b) use of procedural knowledge and problem-solving steps. In the following section, we first present the four low-performing students' improvement in the areas mentioned above, followed by the high-performing students' areas of improvement.

Low-performing students' improvement in accuracy and depth of recalling species concepts. Prior to the pre-interview, in class, students learned species concepts. During the pre-interviews, when the four low-performing students were prompted to recall species concepts - biological species concept (BSC), ecological species concept (ESC), morphological species concept (MSC), and phylogenetic species concepts (PSC), they all revealed low levels of accuracy and depth in their understanding. The similarities among the participants' conceptual understanding were as follows: (a) they only identified some of the species concepts, (b) their descriptions of the identified concepts were vague or unsophisticated, (c) their descriptions included misconceptions, and (c) they expressed confusion.

In the post-interviews, all four students presented an improved understanding of the species concepts. During the post-interview, although some of the students continued to have some confusion about the phylogenetic species concepts (PSC), most of the students demonstrated an accurate and complete understanding of the other species concepts (biological, ecological, and morphological) studied in *SOLVEIT*. The biology problems in *SOLVEIT* did not include data grounded in PSC. All four participants provided more clear and accurate descriptions of the species concepts, and they used more words or phrases that indicated fluency in the concepts. For example, the participants started to use key vocabulary like “hybridization and hybrid population size” and “fertile or viable” for describing biological species concepts.

The case of Shelly. She showed significant improvement in her conceptual understanding of biological species concepts. In the pre-interview, she asked questions rather than making statements and seemed to lack confidence. She did not seem to be very focused. In the post-interview, she presented more accurate explanations of the concepts. These are shown in the following responses from Shelly:

> Researcher: We've learned species concepts in class. Can you tell me what they are and can you define those concepts?
>
> Shelly: [Pre-interview] Species concepts? Let's see…defining species concepts…trying to discern which ones are… uh the…hold on. Biological species means that they are, hold on. I can do this; I know I can. Um, let's see, I'm thinking of the one where they look alike, so they are alike; that's morphological species concept. And, then, we have biological species concepts were that where they use the same resources...is that the right one? Ok, so, they use the same resources in different ways. There's two… what's the last one? [phylogenetic?] Oh ok. Phylogenetic, that's the extent of what I didn't remember.
>
> Shelly: [Post-interview] So, you got the biological, which is if they can reproduce and produce viable offspring that can reproduce as well. And, then, you have your ecological, which is like what kind of…word, hold on…[Niche?]. Yeah, like niche partitioning and all that stuff, like what they use – what resources they use. And, then, you have morphological, which is if they look alike, then they are alike. Then, you have your phylogenetic, which is where you read the phylogenetic tree to see if you have common ancestors and clades and stuff.

Taken together, these findings show considerable gains in students' understanding of species concepts following the use of *SOLVEIT*.

Low-performing students' improvement in using and interpreting evidence. Successful data analysis behaviors include synthesizing and weighing data. On the other hand, unsuccessful data analysis behaviors include using guessing strategies that are not followed up by evidence and overlooking evidence that is provided in the question, often stating that there is no evidence. In the pre-interviews, the four participants presented different types of difficulties in handling the pieces of evidence in the problems.

The three main behaviors in data analysis the low-performing students showed were overlooking and disregarding evidence, misinterpreting evidence, and making an incomplete analysis of the evidence. Students tended to selectively interpret the data with which they were most comfortable or over-rely on the simplest pieces of evidence or the first information they came upon. Students disregarded some evidence that they were not sure how to interpret. Often, they focused only on parts of the evidence that agreed with their current assumptions. Despite clear instructions of the problems, they often did not realize they were responsible for analyzing and providing an explanation of all of the evidence provided.

For example, Olivia and Bella exemplified the first behavior. Bella overlooked evidence because she thought she had already accurately analyzed it, leading her to an incorrect conclusion because she did not include all of the data in her analysis. Olivia decided that two pieces of evidence were enough (representing the morphological species concept, or MSC, and the ecological species concept, or ESC) and did not consider the biological species concept (BSC) data presented in Figure 2 and Table 2 in the Toad problem. In general, when presented with a task that was slightly more complex (e.g., the Toad problem, which required analyzing two pieces of BSC Data as compared to only one in other problems), students were more likely to disregard or overlook one of the pieces of data (Figure 2 or Table 2).

Second, students misinterpreted the evidence in texts, figures, graphs, or tables. Monica often said in her explanations, “I don’t know” “I don’t understand,” “I’m confused,” and “It doesn't mean anything to me." The participants would often use phrases like "I don't know" or "I don't understand" followed by an incorrect analysis of a piece of evidence. Bella demonstrated the second common behavior of low-performing students, misinterpreting data. She was not able to infer that the hybrids are most likely not fertile by seeing the decrease (or lack of increase) of hybrids in Table 2 in the Toad problem.

> Bella [Pre-interview, Toad]: "Table 2 shows that Island and Western toads can interbreed and produce offspring that's fertile because the chart shows that the number of individuals went up. So, they were similar and that…this chart shows that…well, the chart is not really conclusive, because it doesn't show if they're fertile or not, so they can produce offspring, but who knows if they're necessarily fertile or not."

In Shelly's pre-interview, she made an incomplete analysis of the data. "…it [Figure 2] shows that they can reproduce and their population size went up with the western so I'm assuming that they would all three be the same species" She made the mistake of assuming that the figure includes all of the options rather than paying close attention to the labels (note: If she had she paid closer attention to the labels on Figure 2 and Table 2, she would have realized her analysis was incomplete and lead to an incorrect conclusion.)

In addition, of particular note was the difficulty they had in determining the value of the evidence. Some evidence is stronger than other types; these students had great difficulty making that distinction. They also did not synthesize multiple pieces of data to draw a conclusion.

Analysis of data during problem solving improved after the use of *SOLVEIT*. Students considered all or most of the evidence, and they demonstrated less misinterpretation and more complete analyses. Before *SOLVEIT,* students were more inclined to overlook or disregard evidence. After *SOLVEIT,* students considered more pieces of evidence and gave more accurate analyses, though sometimes those analyses were still incomplete. When analyzing the data in the problems or justifying their answers with the data, most of the participants could explicitly refer to the species concept that applied to the data with confidence. They also used scientific vocabulary more fluently as they interpreted the data.

The case of Monica. During the pre-interview, she misinterpreted some of the evidence and became distracted by her own thoughts rather than focusing on what evidence was actually there, but during the post-interview, her response was more clear and focused.

> Monica: [Pre-interview, Toads] "When I go back to look at proportions of them, that still doesn't mean anything to me because I don't understand why it would matter to a species. I mean…the toads are either going to produce or they're not so… if they're there, they're there, if they're not there, they're not there. Also…it didn't talk anything about the island toad here. So, I thought well, maybe the island toad and the Western toad are similar, the same thing, so then…it actually makes me think that they're all the same species just because…maybe the island and the Western hybrids became just…one species and then it was just the hybrid of those versus the Eastern and I mean…it makes it kind of the same."
>
> Monica: [Post-interview, Toads] "Table 2. Yeah since first there were a total of 51 and then second year there was a total of 48 it shows me that there was a decline and that the proportion of it shows that, I mean, it shows that it's not like, I don't know the word. It's not. It's going. It's not viable and it's going down so it's showing if it's the same species it should go up, but since it went down it actually went down of the western and the hybrid. The eastern just stayed the same."

The case of Olivia. During the pre-interview, her analysis of the evidence was incomplete, but during the post-interview, she demonstrated a more complete and correct analysis.

> Olivia: [Pre-interview, Toads] "In the pre-interview she disregarded two major pieces of evidence, both of which pertain to the biological species concept. Based on her analysis, she concluded that all the toads were the same species, but because she disregarded the table and the graph, she did not make the connection that the Island and Western toads were the same species but the Eastern toads were not."
>
> Olivia: [Post-interview, Toads] “Basically it [XXX] says they bred the island and western toad in captivity so it shows they had a small number of hybrids a couple years ago and over time they saw an increase in hybrids so apparently they are making more hybrid population size. Since they produce more hybrids... that’s how I interpret that.”

The case of Bella. During the pre-interview Bella overlooked evidence but after *SOLVEIT,* she examined all of the evidence provided.

> Bella: [Pre-interview] No analysis of evidence associated with the ecological species concept.
>
> Bella: [Post-interview, parasite] “Because ecologically they’re different species because it said that they’re reproductively isolated, no hybridization could be found so they’re ecologically in different locations and regions”

Analysis of the transcriptions from the pre- and post-interviews revealed an improvement in the appropriate use of data and the quality of students' interpretation of data. In the post-interview, the participants were more careful in analyzing different pieces of evidence, as compared to their data analysis during the pre-interview.

Low-performing students' improved problem-solving steps. Students before *SOLVEIT* lacked procedural knowledge, and as such they were not able to devise strategies to solve the problems. Students had a tendency to take an unorganized approach to solving problems. During the pre-interviews, all four participants' answers contained many pauses and ramblings. Most participants plunged into the evidence without reading the problem carefully or engaging in a planning phase.

After *SOLVEIT,* students demonstrated more sophisticated procedural knowledge skills, which they were then able to apply to a forward-focused problem solving strategy. Also, they were able to use a more organized approach to consider the different pieces of evidence and then devise a conclusion.

The case of Monica. Monica showed significant improvement in her problem solving approach. In the pre-interview, Monica noted that she was not very sure about how to solve the problem, and she did not describe the steps she followed explicitly. In the post-interview, she employed more a consistent, sophisticated problem solving and could explicitly express the steps she followed. These are shown in the following responses from Monica:

> Monica: [Pre-interview, Toads] "…then for the hybrids I don't see that as relevant because…I mean…if the two snakes are meeting, obviously that's what is going to happen, it's going to be in the middle there somewhere so…I didn't see that as anything that relates…like the hybrids, maybe that's all the hybrids together are all the same species now but the two separately black and grey are not and then the evidence for the Table 1, the fact that they're similar in numbers of them doesn't mean anything to me because, I mean, I could compare that to like people in the United States, like there's different people but we're not all the same. So, it's like…technically we're all humans

and these are all snakes but some are from African American descent and some are from Asian background. I don't know…I mean, that doesn't mean we're all living in one place together. So, that doesn't mean anything to me."

Monica: [Post-interview, Toads] "For the western and eastern? Not necessarily but since it…I mean, since you do you see after a year it declines, it shows me…at least I see it as not being…it may be fertile but it's not viable, so when figure two it's now comparing island and western toad hybrids, it shows me that the western and eastern don't, but the island and western do. This is enough information to tell me that it's the same species since the morphological description of them for the average length, snout length and body length were similar and the same with the habitat and the food and feeding and it's just the coloration that is different but doesn't necessarily mean it's not the same though it is something to look at."

The case of Bella. In the pre-interview, Bella's description of her problem-solving steps was disorganized. Bella was not sure what she should do to deal with all of the evidence provided. She disregarded evidence and misinterpreted various pieces as well. She was also unable to connect the pieces she did analyze to each other or to provide a response that matched the instructions. In the post-interview, Bella could explicitly describe the steps she followed, and Bella's description of her problem-solving process was more focused, efficient and concise compared with her rambling responses in the pre-interview:

Researcher: Okay. Can you describe the steps you used to arrive at your answer?

Bella: [Pre-interview] "Well, I know they're morphologically…wait…is it asking… oh wait, maybe that's not my answer…I know they're morphologically the same species, because they all look the same. [Okay] But, then, you can't really prove from this map if they're ecologically the same because it's different areas. And, then, from the evolutionary tree…I don't know…would they be the same species? I don't know. I know they all come back to this original node…and branch off. And, then, you don't really know biologically, because it doesn't say if they interbreed."

Bella: [Post-interview] "Well, first, I decided what species concepts would be represented, and it's the morphological and phylogenetic. And, so, and I know, according to morphological, they're different species. They don't look alike, and then again, according to phylogenetic species concept, they're different species."

High-performing students' improvement in accuracy and depth of understanding of species concepts. The four high performing students showed decent conceptual understanding during the pre-interviews and improved, more accurate understandings of the species concepts during the post-interviews after *SOLVEIT*.

The case of Blair. Prior to *SOLVEIT,* Blair was able to accurately recall the three species concepts she was prompted to define and in some cases used advanced domain knowledge. For example, in pre-interview, Blair indicated "There's biological, which means …Ok, meaning if they can reproduce and then their offspring can also have offspring" After *SOLVEIT*, in post-interview, she accurately recalled all four species concepts and frequently used advanced domain terminology: "Biological states that two organisms of the same species should be able to produce offspring or produce viable and fertile offspring."

The case of Ethan. Prior to *SOLVEIT,* he demonstrated a range of understanding of the concepts, from complete misunderstanding ("biological means that they have the same genetic makeup") to utilizing advanced terminology ("ecological species concept is that they live in the same niche, eat the same kind of foods, and things like that"). After *SOLVEIT*, he articulately described the four concepts and utilized advanced terminology throughout. For example, "biological is whether or not they have viable and fertile hybrid offspring."

The case of Jessica. Prior to *SOLVEIT,* Jessica had the highest level of domain knowledge of all the participants. She often used advanced terminology and backed up her definitions with real world examples to show that she really did understand the concept as opposed to having just memorized it.

> Jessica: [Pre-interview] "Then you have the biological species concept which I thought…the most helpful one is someone who is not a biologist and it's very interesting to learn about that one…that idea is that two things have to be able to breed together and then the children that they produce also have to be able to breed, they have to viable. So, I know you can breed a horse and donkey together and you get a mule, but the mule isn't a species because it can't go on to reproduce more stuff."

After *SOLVEIT*, her definitions became shorter and more concise. For example, "…ecological species concept is organisms sharing the same niche are the same species" She had acquired more advanced terminology. She seemed comfortable and at ease providing these definitions.

The case of Serena. Prior to *SOLVEIT,* Serena's definitions of the concepts were short and in some cases incomplete. She could not remember the name of one of the concepts. For example, "And then the last one which I can't remember the name of, but it's when they share the same strains of DNA or similar strains, and they have the different family trees that branch off." After *SOLVEIT*, most of Serena's definitions improved and she increased her use of advanced domain terminology. She still had one incomplete definition of one of the concepts ("the biological species concept is that two species can hybridize and have fertile offspring").

High-performing students' improvement in using and interpreting evidence.

The case of Blair. Prior to *SOLVEIT*, despite having accurate recall of the necessary domain knowledge, she misinterpreted pieces of evidence in both of the questions (Snake and Toad), which, in conjunction with her lack of evidence value assessment, led her to incorrect conclusions in both cases. After *SOLVEIT*, she demonstrated improvement in her ability to accurately analyze the provided evidence. Her conclusion statements were more complete and led her to better synthesize the evidence into a conclusion, though she was inclined to declare that the relatedness of the species could not be determined rather than place a value assessment on the evidence, i.e., the biological species concept is more valuable than the morphological species concept if given both types of evidence.

> Blair: [Pre-interview, Snake]: "...And then I said based on the biological species concept they are the same species because you can see in table 1 that they had offspring and their offspring were able to produce as well. At least in seven cases. For the morphological it would seem that they are different species because the black rat snake is considerably smaller than the gray rat snake and they are different colors. Then for the ecological they have the exact same eating habits, so they would be the same."
>
> Blair [Post-interview, Parasite]: "…you can gather information from the ecological because it says that they habitat different environments because if one lives in white and one lives in red blood cells, so that would say they're different based upon the ecological."
>
> Blair [Post-interview, Toad]: "And then in Table 2 it says that they, it doesn't say whether or not they could produce fertile offspring, like they had offspring, but it doesn't

say if they were fertile or not. So I guess you could say the Eastern can't be determined, not necessarily different."

<u>The case of Ethan.</u> Prior to *SOLVEIT,* he analyzed some evidence well, misinterpreted and even overlooked some evidence, and misinterpreted a comment in the instructions as referring to a species concept that wasn't included in the problem. In the Toad problem, he overlooked an entire figure. In both cases, his misinterpretations involved the biological species concept.

> Ethan [Pre-interview, Snake] "...phylogenetic, right now they are members of the same species, let's see …???. So I put them down as the same in phylogenetic, because they would be sharing a branch on the tree."

After *SOLVEIT*, his analysis improved greatly; he correctly applied his domain knowledge as well as his problem representation to the evidence, and he evaluated all evidence provided while weighing its value.

> Ethan [Post-interview, Toad]: "Biological Figure 2 shows us that the hybrids worked out very well between Western and Island Toads so that's a yes for biological…biologically they had very few hybrids and very little noticeable success between hybrids, so I put no."

<u>The case of Jessica.</u> Prior to *SOLVEIT,* Jessica did a good job analyzing the evidence. She did misinterpret some of the evidence but she was not far from the correct answer. Additionally, she said what further evidence she would like to have had to make the argument stronger, indicating a more in-depth knowledge of the concepts and of how to review the evidence.

Jessica [Pre-interview, Snake]: "Ecologically speaking, there is some evidence because they do eat small mammals, birds, and bird eggs which we see in Table 2. I'd like to see a little more evidence about where they live and where they're found which would be interesting to know but there's still good evidence and probably would be a good claim."

After *SOLVEIT*, Jessica easily and accurately moved through the different pieces of evidence in the Parasite question. In the Toad question she still had a little difficulty dealing with the fact that there were multiple pieces of evidence about one species concept, which led her to incompletely analyze the evidence. However, she did accurately analyze the rest of the data.

Jessica [Post-interview, Parasite]: "Biologically this is table 2 we see data on how they try to hybridized and we see that they don't hybridized in nature and it failed in lab as well."

Jessica [Post-interview, Toad]: "That one I looked at is that it was good biological evidence that the island western are the same since the hybrids were isolated and its number was increasing. So at least those two were biologically the same."

High-performing students' improvement in problem-solving steps.

The case of Blair. Prior to *SOLVEIT*, in the pre-interview, data indicated she utilized a step-by-step method of problem solving in which she considered each piece of evidence. After *SOLVEIT*, in the post-interview, results from data analysis indicate that Blair more carefully examined each piece of evidence and came to a correct conclusion for each individual piece.

The case of Ethan. Prior to *SOLVEIT*, in the pre-interview, data indicated his ability to apply procedural knowledge seemed inconsistent. He considered most of the evidence but overlooked some of it and completely fabricated one piece of evidence. After *SOLVEIT*, in the post-interview, results from data analysis indicate that he applied his initial graphical representation directly to the data provided in a clear and organized manner.

The case of Jessica Prior to *SOLVEIT*, in the pre-interview, Jessica used a step-by-step plan to move through all of the evidence in the Snake question, but for the Toad question, she overlooked or perhaps misinterpreted what she saw, which was that the number of hybrids decreased over two years, indicating that they most likely were not fertile. Instead she decided that other evidence was strong enough that she could ignore that fact.

> Jessica [Pre-interview, Toad] "It doesn't really say anything about the Eastern toads, the only other piece of evidence we'd want to see would be whether or not the Western/Eastern hybrids could breed as well, that would be nice to know. But the evidence seemed pretty strong biologically…"

After *SOLVEIT*, Jessica approached the problem in a clear and forward-moving manner that led her to a correct conclusion.

The case of Serena. Prior to *SOLVEIT*, in the pre-interview, Serena approached the problem in a forward-focused manner and considered all evidence. After *SOLVEIT*, she used a clear and concise forward-focused method to analyze the evidence, so much so that she even disregarded evidence that she determined held little value.

Conclusions and Discussion

The findings about college students' problem-solving skills from this study are consistent with previous research studies regarding novice problem-solving performance (e.g., Chi, Feltovich, & Glasner, 1980). Data indicate that participants employed a wide range of unsuccessful problem-solving skills as they solved the provided biology problems.

Overall, the findings revealed that most of the participants were able to solve science problems more successfully after engaging in scaffolded problem solving in *SOLVEIT.* By the end of *SOLVEIT,* those students who initially presented low-level conceptual understanding and problem-solving processes demonstrated an improvement in their problem-solving skills.

Specifically, the findings from the qualitative case study show that the participants gained content and procedural knowledge, improved reasoning and data analysis skills, and were more concerned about developing sound conclusions. Their problem-solving efforts were also more well-structured and holistic. There were variations in the levels of students' skills while solving problems after using *SOLVEIT*; most students showed a significant improvement in various aspects of problem solving, but some of them still showed some reasoning errors while solving problems. The main Similarities and differences between low- and high-performing students' domain knowledge and problem-solving skills before and after *SOLVEIT* are as follows.

- Participants demonstrated different levels of prior domain knowledge of species concepts. Whereas low-performing students (n=4) defined species concepts incorrectly or showed naive and incomplete understanding of the concepts, high-performing students (n=4) showed moderate understanding of the concepts before using *SOLVEIT*.
- Most high-performing students showed decent conceptual knowledge and well-structured procedural knowledge while problem solving both before and after using *SOLVEIT*.
- In the pre-interviews, low-performing students demonstrated low levels of data analysis skills prior to *SOLVEIT* - e.g., disregarding or overlooking evidence; after completing *SOLVEIT*, they showed significantly improved data analysis skills in the post-interviews.
- High-performing students showed moderate data analysis skills, but they sometimes misinterpreted evidence in the pre-interviews; after completing *SOLVEIT*, they used appropriate data analysis skills most of the time in the post-interviews.
- Students went through well-organized problem-solving steps while solving biology problems after completing *SOLVEIT*.

Despite the different gains between the participants, a similar pattern of findings recurred in all of the participants as mentioned above. Overall, the data indicates that *SOLVEIT* helps students acquire desirable problem-solving strategies. Also, students reported the question prompts for conceptual understanding in *SOLVEIT* helped them identify the important concepts of the problem, fix their misconceptions, and apply the concepts to actual problems. Interestingly, Monica, a low-performing student, who used *SOLVEIT* more intensively showed more improvement in her knowledge and skills than Bella who reported she did not put a lot of efforts into the completion of *SOLVEIT*. As a result, Bella showed the least improvement in her problem-solving skills. This conclusion is consistent with previous research studies on computer-based scaffolding, which suggest that computer-based scaffolding can improve students' cognitive skills in solving problems (Belland, 2010; Singh & Haileselassie, 2010).

Low-performing students believe that most science problems are too difficult for them to solve; they lack confidence and previous experience, as well as sufficient background knowledge and skills. Hence, low-performing students require a great deal of practice in order to develop their expertise. Therefore, science teachers may need to place more emphasis on using some available computer-based tutorials or designing and implementing computer-based scaffolding in addition to teaching problem-solving skills in class. Teachers can then focus more on improving students' skills, including metacognitive abilities, while computer-based scaffolding can help students to enhance declarative and procedural knowledge for problem-solving success.

Some researchers have been concerned with designing effective computer-based metacognitive support (Azevedo, 2005; Quintana, Zhang, & Krajcik, 2005). However, it is difficult to design effective computer-based metacognitive scaffolding that teaches students what to reflect on in their work, what questions to ask themselves, and when reflection is appropriate.

Providing appropriate scaffolding for monitoring one's own problem solving is challenging for computer-based tutorials (Belland et al., 2008). Moreover, it is easy for students to neglect prompts for reflection and monitoring in computer-based tutorial programs. Teachers' metacognitive support may be more effective than computer-based metacognitive support. Teachers need to emphasize more deliberate problem solving with complex tasks so that students will be able to better reflect on their problem-solving processes. *SOLVEIT* could be implemented in class as a supplementary tool to support college science teachers' lectures or class activities.

Study Limitations and Future Research

Two limitations inherent in this type of research are described. First, the range of problem-solving tasks is narrow. Problems in the pretest, posttest, and *SOLVEIT* have similar level of difficulties, similar structure and complexity and surface differences. The problems relevant to species concepts are those for which students previously had difficulty drawing a correct conclusion. Detterman (1993) views contextually similar problems as "near transfer tasks" or "within-task transfer problems" and contextually dissimilar problems as "far transfer tasks" or "applied problems." Contextually dissimilar problems have different structures and require different domain knowledge and skills. The findings do not show whether students can apply learned problem-solving skills through scaffolded *SOLVEIT* to different types of problems. Far transfer is often presented in experts' performance, whereas novices often fail to transfer their knowledge and skills to new problems or situations. An additional limitation is that *SOLVEIT* was only tested in an introductory biology course. Each introductory biology course is unique in terms of its content, goals, and students' level of performance, so further research is required to examine if implementing *SOLVEIT* results in similar learning gains or desirable outcomes in different contexts. In sum, we need further research to investigate how *SOLVEIT* influences students' problem solving with contextually dissimilar problems and if implementation of *SOLVEIT* in a different context still results in significant learning gains. Additional studies on the design of computer-based scaffolding will be needed to determine how to promote the transfer of problem-solving skills to different types of problems.

Despite these limitations, this study demonstrates, overall, the potential of *SOLVEIT* to enhance conceptual understanding and problem-solving processes required for science problem solving. More studies are needed to develop a deeper understanding of how computer-based scaffolding can contribute to improved learning and performance in science problem-solving domains.

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CHAPTER 5

CONCLUSIONS

The overall aim of this research was to advance theory and practice in computer-based scaffolding for improving students' problem-solving abilities in a college science education context. Specific goals were to (a) create a reliable and effective computer-based instructional intervention for the improvement of college students' problem solving in science and (b) generate a sustainable scaffolding model supported by both theoretical and empirical evidence. To facilitate these goals, educational design research (EDR, also known as design-based research) methodology (McKenney & Reeves, 2013) was employed. Some have questioned if there is a difference between EDR and formative evaluation (van den Akker, Gravemeijer, McKenney, & Nieveen, 2006). While EDR and formative evaluation may be similar in some ways - e.g., both can be used for developing an instructional innovation that resolves educational problems, the EDR process used for this study differs from formative evaluation in the following ways:

- This EDR study addresses the *complex* educational problem of how to develop students' science problem-solving skills using computer-based scaffolding, in which many science education researchers and practitioners are interested.
- People who have different expertise (e.g., biology educator, instructional designer) are engaged in this EDR study. Efficient communication and close collaboration between researchers, practitioners, and stakeholders are essential for successful EDR (DBRC, 2003; McKenney & Reeves, 2013).

- This EDR study addresses *theoretical questions* about the functions and mechanisms of computer-based scaffolds that facilitate science problem solving. This EDR study aims at understanding not only an educational innovation (*SOLVEIT,* introduced later) in practice but also the relations between scaffolding theory and the innovation to refine current scaffolding theory and models (c.f., theory generation is not a goal of formative evaluation) (Barab & Squire, 2004; Wang & Hannafin, 2005).
- This EDR study aims for the development and *evolution* of *SOLVEIT*. *Rigorous formative evaluation* is adopted as a method of this EDR study to observe how *SOLVEIT* functions and to test and refine it in a real, *authentic* educational context. In general, EDR highlights continuous refinement of an intervention through iterative cycles of design, implementation, evaluation, and redesign (van den Akker et al., 2006).
- This EDR study considers insights for future research and puts emphasis on the generalizability of the outcomes and an innovative tool applicable to other areas (Barab & Squire, 2004).

The EDR process used for this study is as follows (adapted from McKenney & Reeves, 2013, see Figure 5.1). First, grounded in the review and analysis of previous theoretical and empirical research on scaffolding strategies, a conceptual scaffolding design framework was created. The conceptual framework was proposed to guide the design of computer-based scaffolding for supporting science problem solving. Second, a self-directed online tutorial program, *SOLVEIT,* aligned with the framework, was designed and developed by an interdisciplinary team of researchers (instructional design, biology and computer science). *SOLVEIT*, which provides various scaffolds (e.g., visual guidance, question prompts, immediate feedback, etc.), was created to address college students' problem-solving difficulties as they seek to understand and explain scientific phenomena as well as challenges of college instructors who teach problem-solving skills in large-enrollment college science classes. We then evaluated the effects of *SOLVEIT* on the enhancement of problem-solving skills in the context of college science education. Until now, two empirical studies were conducted in a large introductory biology course for non-majors to clarify the scaffolding design framework and examine the effects of *SOLVEIT*. Overall, the findings from the two empirical studies provided evidence to support the potential efficacy of a computer-based scaffolding approach to science problem solving.

SOLVEIT as well as the design guidelines and principles in the suggested scaffolding framework are formative. They should continue to be refined and expanded through additional research studies in various settings to be implemented easily and best support students in other science disciplines as well as biology. This iterative approach is usual based on what has occurred with other scaffolding tools in science as well as other educational contexts (Bell, Hoadley, & Linn, 2004; Bereiter, 2002; Burkhardt, 2006).

The following sections are organized as follows. First, I present the main findings from the two empirical studies and suggestions for refining the current version of *SOLVEIT*. Based on the findings, I provide some implications for designing effective computer-based scaffolding for facilitating science problem solving. Then, I indicate future research and present the conclusive remarks.

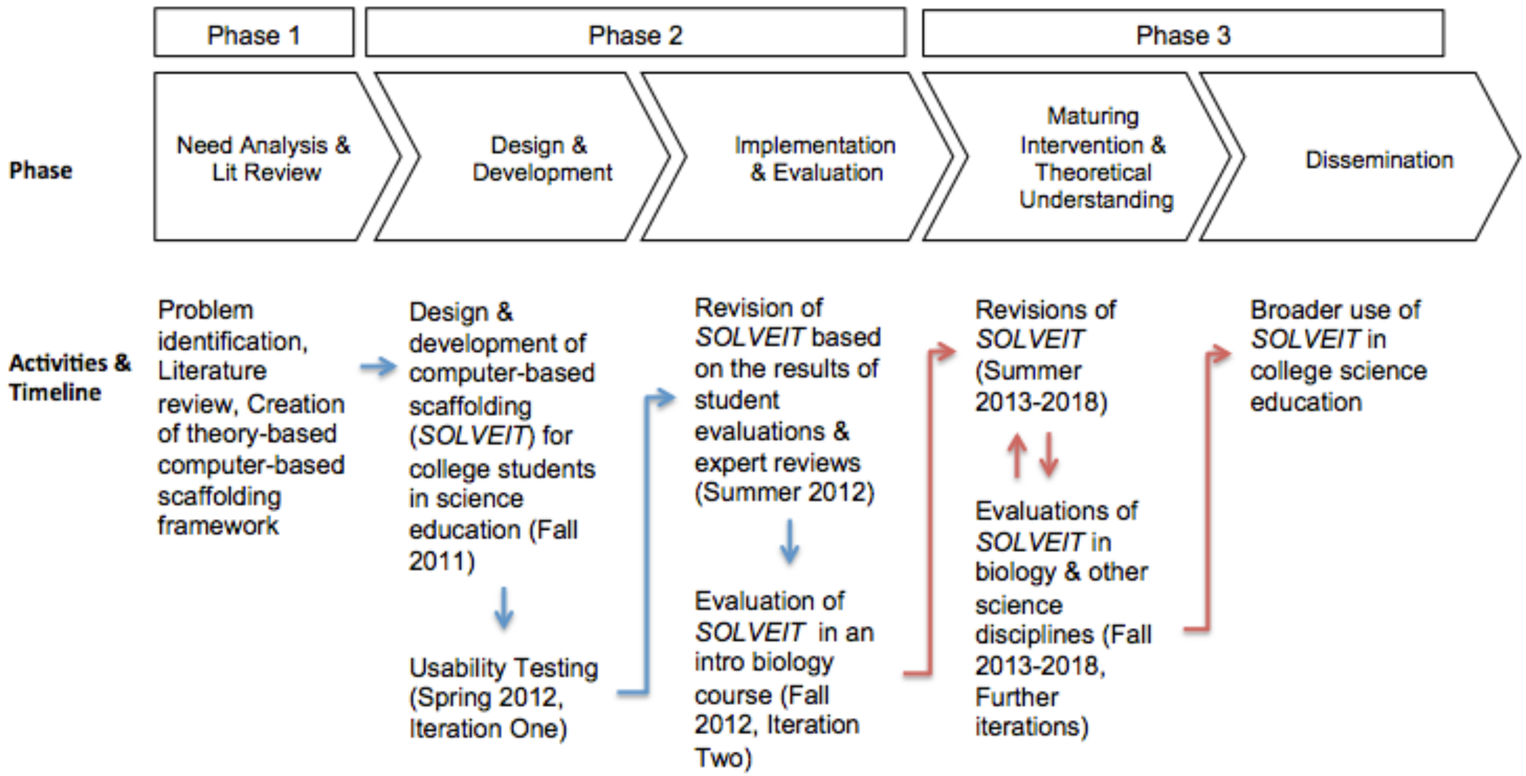

Figure 5.1. Phases in this educational design research and main research activities (Adapted from McKenney & Reeves, 2013). The blue arrows indicate complete activities and the red arrows indicate upcoming activities to be conducted in future research.

Key Findings from the Two Iterations and Refinement of *SOLVEIT*

To explore how students perceive their use of the scaffolds in *SOLVEIT* and their learning gains, qualitative case studies were employed, and the data from the *SOLVEIT* database and students' self-reports via survey and interviews (n=6) were analyzed (the first iteration of *SOLVEIT* in Spring 2012). The following description summarizes the major findings from Iteration One:

- Overall, students considered *SOLVEIT* a useful learning program.
- *SOLVEIT* was helpful for improving their understanding of the important concepts (e.g., species concepts) in the problems and correcting their misconceptions about the concepts (database, interview).
- Students reported they were able to appropriately analyze evidence after using *SOLVEIT* (interview).
- The step-by-step guidance using question prompts and immediate elaboration feedback for problem-solving processes (Phase 3) was considered strong features of *SOLVEIT,* and students reported that this feature influenced the advancement of their understanding of problem-solving processes (interview).
- In *SOLVEIT*, students responded to metacognitive question prompts asking what thinking skills were used in their problem-solving processes, but they provided rather simple answers in response to the prompts (database).
- Some students overlooked the optional features of *SOLVEIT* - e.g., many students did not know the existence of expert models in Phase 6, a student reported that the length of the additional interactive tutorials in Phase 3 were too long to review, and another student reported that she already knew the information in the tutorials (interview).

- The reported weaknesses of *SOLVEIT* were as follows: (a) The length of Phase 1 through Phase 6 was considered inconvenient - students reported *SOLVEIT* included too many constructed-response questions; (b) the limited amount of content was considered a weakness; and (c) students reported the prompts for evaluating their initial answers (metacognitive scaffolds in Phase 4) were unnecessary (interview).

Informed by Iteration One, most features of *SOLVEIT* were kept and only minor revisions were made to the scaffolds:

- Though students reported that the prompts asking for reflection on initial answers (Phase 4) were a weak feature of *SOLVEIT*, Phase 4 was kept because reflection is an important step of problem solving.
- All question prompts through the phases were refined, and redundant question prompts were revised. Consequently, the length of *SOLVEIT* was a little shortened.
- Unclear instructions and feedback for the optional features were modified.
- Reminder messages were added for encouraging students to use the expert's models provided as an optional scaffold in Phase 6.

It is noted that we characterized the findings from Iteration One as limited because this study was conducted on a small scale, and most major findings were from the participants' self-reports. Therefore, major redesign or modifications to the scaffolding in the six phases of *SOLVEIT* will be made according to the findings (e.g., students' actual learning gains) from Iteration Two.

To investigate the impact of the scaffolds in *SOLVEIT* on students' problem-solving skills, a mixed methods study (the second iteration of *SOLVEIT* in Fall 2012) was employed. The collected data sources were the *SOLVEIT* database, surveys, instructor-developed pre- and post-tests, and the test of scientific literacy skills (TOSLS, Gormally et al. 2012) of 149 students and 16 students' pre- and post-interviews. Our initial data analysis included 8 students' pre- and post-interviews, database, and survey. The following description summarizes the major findings from the initial data analysis in Iteration Two:

- Overall, students indicated that they considered *SOLVEIT* a useful learning program (post-interview, post-survey).
- Participants demonstrated different levels of prior domain knowledge of species concepts. Whereas low-performing students (n=4) defined species concepts incorrectly or showed naive and incomplete understanding of the concepts, high-performing students (n=4) showed moderate understanding of the concepts before using *SOLVEIT* (pre-interview and pre-test).
- The question prompts for conceptual understanding helped the low-performing students identify important concepts of the problem and fix their misconceptions and apply the concepts to actual problems; all showed significant or slight improvement in articulating domain knowledge after completing *SOLVEIT* (post-interview and post-test).
- Low-performing students demonstrated low levels of data analysis skills prior to *SOLVEIT* - e.g., disregarding or overlooking evidence (pre-interview and pre-test); after completing *SOLVEIT*, they showed significantly improved data analysis skills (post-interviews and post-test).
- High-performing students showed moderate data analysis skills, but they sometimes misinterpreted evidence (pre-interview and pre-test); after completing *SOLVEIT*, they used appropriate data analysis skills most of the time (post-interviews and post-test).

- Students went through well-organized problem-solving steps while solving biology problems after completing *SOLVEIT* (post-interview).
- Step-by-step guidance with question prompts and immediate feedback showed low-performing students how to approach a problem to reach a solution and helped in evaluating possible solutions (post-interviews).
- High-performing students gave more reflective answers to the questions about their thinking skills than low-performing students in response to the metacognitive prompts in *SOLVEIT*; regardless of levels of students' performance, a few students (n=3) did not use the metacognitive prompts appropriately (database). The students reported they did not know exactly how to respond to those kinds of prompts (post-interviews).
- Overall, more students reported self-monitoring and self-evaluation behaviors on their problem solving during the post-interview than during the pre-interview.

Based on the findings from Iteration Two (as well as Iteration One), some scaffolding features of *SOLVEIT* will be revised and refined in the near future. During this process, we will eliminate the unhelpful features that detract from learning and retain and improve the helpful features.

- Overall, *SOLVEIT* will be made more adaptive to students' levels of performance/skills; the amount and types of scaffolding should be matched with the level of prior knowledge and skills of students; simply put, *SOLVEIT* will provide more problems and scaffolds for low-performing students than for high-performing students.
- *SOLVEIT* will track students' progress as they solve problems.
- As students develop their problem-solving skills over time, either scaffolding will be continuously faded or students’ autonomy in selecting scaffolding will be increased;

- Metacognitive scaffolding (reflecting on their thinking skills) may be more closely connected to students' actual problem-solving processes in Phase 3 (e.g., pop-up metacognitive messages or questions connected to a student's domain-related incorrect answers).
- *SOLVEIT* will be extended to include problems on protein structure function and metabolism.
- Motivational messages will be added for metacognitive scaffolds.
- The current *SOLVEIT* incorporates many self-explanation prompts. These prompts may be combined with elaboration feedback for low-performing students.
- In addition, we will make *SOLVEIT* more administrator-friendly so that instructors/TAs can easily assign tasks to students through *SOLVEIT* and track student progress.

More specific revision plans for *SOLVEIT* are shown in the future research section. In the next section, I present implications for designing computer-based scaffolding for science learning derived from systematic investigation in Iterations One and Two.

Implications for Computer-Based Scaffolding Design

Several implications are drawn from the findings for researchers, instructional designers and college instructors who design and implement computer-based scaffolding for science learning. Implications are categorized by the function of scaffolds.

Scaffolds for Conceptual Understanding

In-depth content knowledge is necessary for science problem solving (Shin, Jonassen, & McGee, 2003). The level of domain knowledge is important because it may influence one's confidence in solving problems. Expert possess well-organized domain knowledge (Reif, 2008); in contrast, many novice students often show surface-level understanding in domain knowledge

(Larkin, McDermott, Simon, & Simon, 1980). In this study, initially, low-performing students presented inaccurate and unsophisticated understanding in the domain of species concepts. Low-performing students showed significant improvement in accurately recalling those concepts and applied the concepts to different biology problems more appropriately after using *SOLVEIT*. Regardless of performance level, all participants showed a more accurate and coherent understanding of species concepts and fewer misconceptions after using *SOLVEIT*; high-performing students showed slight improvement, as their understanding was already moderate prior to *SOLVEIT*. Overall, the findings of this study indicate computer-based conceptual scaffolding via question prompts and immediate feedback in a problem-solving context can be successful for teaching complex science concepts for any level student.

Question prompts have been used effectively as the main instructional strategies for enhancing students' conceptual understanding (e.g., Ge & Land, 2003). Question prompts should be designed to help students differentiate similar concepts, explain the relationship between the main components of a complex concept, and notice and revise their misconceptions. Previous research studies indicate that many students are resistant to changing their misconceptions about science (e.g., Clement, 1982; Andrews et al., 2012). Similarly, in this study, though low-performing students showed significant improvement in understanding, they still showed a few misconceptions after *SOLVEIT*. Therefore, more scaffolding and more types of scaffolding may be necessary for low-performing students. Low-performing students may need both timely and immediate feedback and fairly extensive elaboration feedback on their domain knowledge. Some research studies provide evidence that suggest timely and immediate feedback is effective in learning outcomes in the context of higher education (Pridemore & Klein, 1991). However, if feedback is provided immediately for verification purposes, some students might only focus on finding the correct answer quickly. This is a common phenomenon for novice problem-solvers. Therefore, feedback should be designed to help students think about *why* the selected response is correct or incorrect because reflection on their answer may lead to a deeper understanding and a transfer of knowledge to the problem.

Visualization tools such as simulations are often used to facilitate understanding of a certain phenomenon by visualizing it in science education (e.g., weather change, the earth's rotation and revolution around the sun, etc.). Also, in simulations, students can understand scientific phenomena by repeatedly manipulating relevant parameters in a situation. Korkmaz and Harwood (2004) designed and developed an interactive Web-based 3-D learning environment in which first year chemistry students examined, rotated, and moved molecules to understand the molecular structures and symmetry elements within a closed set of molecules. Students found the tutorial valuable in learning symmetry elements on three-dimensional molecular structures through on-screen manipulations. Simulations can improve the depth and quality of the domain knowledge of students while engaging them in solving realistic problems. However, a literature review study conducted by Ma and Nickerson (2006) reports mixed effects of science simulations in higher education contexts. That is mainly because the dynamic features of simulations might cause cognitive overload for students who have sufficient prior knowledge (Betrancourt, 2005). Therefore, more research is required to use visualization tools as conceptual scaffolds for low-performing students.

On the other hand, some higher-performing students in this current research reported that they used some question prompts related to concepts not to acquire new knowledge, but merely to confirm what they already knew. A large number of question prompts might increase students' cognitive load as well. Higher-performing students may feel many question prompts related to concepts they already know are unnecessary and interruptive. Conceptual scaffolds may be provided as an optional feature for higher-performing students who have sufficient domain knowledge (e.g., Simons & Klein, 2007).

Scaffolds for Problem-Solving Steps

Solving science problems is a demanding task for many college students, partially because many of them do not have sufficient skills for approaching science problems in a systematic way (Hogan, 2002; Zeineddin & Abd-El-Khalick, 2010). Question prompts can guide students' engagement in systematic problem-solving steps. For example, students engage in articulating causal processes by responding to reasoning questions (Graesser, Swamer, Baggett, & Sell, 1996).

In this research, initially, Low-performing students tried guessing in order to find an answer. After using the mandatory step-by-step guidance combined with question prompts and feedback in *SOLVEIT,* students analyzed data and drew conclusions more systematically. Students still exhibited a few misinterpretations of evidence and incomplete analysis. The low-performing students reported the step-by-step guidance was the best feature of *SOLVEIT,* and they expected more practice with different types of biology problems with the guidance. The findings suggest that step-by-step guidance in problem solving helps low-performing students focus on and employ important processes for solving a problem and possibly improve their procedural knowledge. However, they may need additional scaffolds.

On the other hand, high-performing students in this study reported they could complete the task without the step-by-step scaffolding, though they also considered the feature positive. High-performing students also showed decent problem-solving steps before *SOLVEIT*. Overall, the findings indicate that high-performing students who already have sufficient procedural knowledge may need simplified and optional guidance.

Different amounts of scaffolding are required to enhance students' procedural knowledge based on learners' levels of ability (e.g., Demetriadis, Papadopoulos, Stamelos, & Fischer, 2008; Raes, Schellens, de Wever, & Vanderhoven, 2012). While lower-performing students may need more time and practice with sufficient scaffolding to enhance their problem-solving processes, providing step-by-step guidance as optional for high-performing students would be enough. In the Web-based Inquiry Science Environment (WISE) (Linn, 2000), students have to complete tasks in a step-by-step manner, and they cannot skip any steps. In contrast, some tools like *Hypothesis Scratchpads* provide templates as optional features (van Joolingen, de Jong & Dimitrakopoulou, 2007). High-performing students who have sufficient procedural knowledge may feel that tools like *Hypothesis Scratchpads* tools are more convenient for them. We need more empirical research studies about how to design step-by-step guidance to help students who have different levels of abilities internalize procedural knowledge in a productive and efficient way.

Scaffolds for Metacognitive Regulation

Metacognition refers to skills for regulating cognitive processes required for learning (Flavell, 1979). Experts are able to plan their problem solving in advance, notice where they make errors by constantly monitoring their problem solving processes, and evaluate their answers to generate the best one. In contrast, most novice students are not accustomed to complex science problems that require metacognition (Tanner, 2012). Evaluating progress toward the goal of problem solving and monitoring problem-solving process are important for drawing a correct or acceptable conclusion or answer. After finding an answer, checking if it is correct is also a form of metacognition (Zimmerman, 2000). Consequently, a deficiency in metacognition can impede students' success in solving complex science problems.

Results from this study also indicate that use of metacognition was challenging for college students, particularly lower-performing students. In *SOLVEIT,* metacognitive question prompts are mandatory, and they are provided after each problem is solved (e.g., what were the main three skills you used to solve this problem?). Some participants in this study reported that they were annoyed by the metacognitive questions in *SOLVEIT* because they did not know why they had to answer these questions. Many students' answers to the metacognitive question prompts in *SOLVEIT* did not contain much detail; this was the case regardless of performance level. This finding indicates that (a) computer-based metacognitive scaffolding may not effective in general because it is not adaptive to each learner's needs (e.g., Belland, Glazewski, & Richardson, 2008); (b) metacognitive support may not be effective when it is separated from the actual problem-solving context*;* or, (c) metacognitive scaffolding may not be used effectively when students do not recognize the benefits of the scaffolding.

Computer-generated question prompts can function as metacognitive support during problem solving (Zellermayer, Salomon, Globerson, & Givon, 1991). According to Lin and Lehman (1999), metacognitive prompts in a computer-based simulation program help students learn how to control variables in biology experiments. The previous research on the effect of computer-based metacognitive scaffolds presents confounding findings. Oliver and Hannafin's (2000) research study on the scaffolds used in a computer-based tutorial (*WISE*) found that students did not respond to the question prompts asking how or why for articulation and reflection purposes. However, some researchers report positive effects of metacognitive scaffolding on learning. Azevedo and Hadwin (2005) found that computer-based metacognitive scaffolds fostered students' learning by encouraging them to regulate their learning themselves. More research is needed to design effective metacognitive scaffolds. In the next section, a new *SOLVEIT* framework grounded in the findings and the scaffolding literature is presented.

Future Research

New Adaptive *SOLVEIT* Framework

Though the current *SOLVEIT* was effective in enhancing students' problem-solving skills, the previous studies revealed some limitations of the program. For example, some students used *SOLVEIT* in non-productive ways (e.g., they provided non-reflective, simple answers to some metacognitive question prompts, or they ignored some optional features of *SOLVEIT*). While keeping most of its current scaffolding features, we will modify the non-productive features of *SOLVEIT*. Another limitation was that the current *SOLVEIT* treats all students the same way regardless of their prior knowledge and skills. Some high-performing students reported that they merely used *SOLVEIT* to confirm what they already knew and the problems in *SOLVEIT* were overly easy, whereas some low-performing students reported that they expected more practice with different types of problems in *SOLVEIT*. As a result, *SOLVEIT* was more effective for low-performing students than high-performing students.

We will address the limitations of the current *SOLVEIT* by adding new features: (a) different difficulty levels of problems in various contents and (b) *adaptive* and *faded scaffolding* provided according to a student's level of prior knowledge. The adaptive design will be accomplished by utilizing pre-assessments (e.g., a measurement for scientific literacy skills) and ongoing tracking of student progress (e.g., time spent on answering a question, the amount of scaffolding used).

The following shows the flow in the new *SOLVEIT* framework (See Figure 5.2):

A. *Selection of content* - *SOLVEIT* will allow students/instructors to select specific content to explore according to their interests (e.g., the domains of protein structure and function).

B. *Mandatory pre-assessments* - Students will take assessments for (a) depth of domain knowledge and (b) scientific literacy skills in the beginning of *SOLVEIT*. The initial assessments will provide the basis for *SOLVEIT*'s adaptability. *SOLVEIT* will use information in the assessments, along with student information (e.g., current grade in the course) to rank students' abilities from C (low-ability) to A (high-ability) and determine a personalized problem-solving path appropriate to the student's prior knowledge (see more details in section D below).

C. *Level/complexity of problems* - *SOLVEIT* will provide different sets of problems in the domains of important content in post-secondary biology/biochemistry (e.g., metabolism). Each set of problems will have three levels of complexity (easy, intermediate, difficult), consistent with the notion of graduated complexity (Milrad, Spector & Davidsen, 2003).

D. *Personalized problem-solving path* - *SOLVEIT* will generate a personalized problem-solving path that includes an estimated time to complete the path and a visualization of the path. For example, in response to the results of the pre-assessments, a low-performing student will start *SOLVEIT* with relatively easy problems with a large amount of scaffolding and then move to intermediate/difficult problems with less scaffolding (a longer problem-solving path). A high-performing student, on the other hand, will have autonomy to choose the difficulty/complexity level of problems, or *SOLVEIT* will suggest a relatively shorter problem-solving path starting from difficult problems. Providing personally appropriate levels of problems and scaffolding may lead to improvement in perceived relevance, confidence and satisfaction as well as overall problem-solving performance.

E. *Scaffolded problem solving* and *fading of scaffolds* - Students will practice solving science problems with multiple forms of scaffolds in *SOLVEIT* (e.g., step-by-step guidance as strategic scaffolds). As students progress, scaffolds will be faded continuously. The concept of fading support as students make progress has been promoted in the literature since Collins, Brown, and Newman (1989) developed the instructional approach called cognitive apprenticeship. Cognitive apprenticeship through modeling, scaffolding, fading, and coaching has been successfully implemented in teaching science problem solving (e.g., Heller, Keith, & Anderson, 1992) in the contexts of K-12 and post-secondary education as well as complex tasks in general education contexts. The new *SOLVEIT* scaffolding design will be more aligned with the cognitive apprenticeship model.

F. *Ongoing tracking of student progress and coaching for problem solving - SOLVEIT* will automatically track, record, and analyze students' problem-solving paths (e.g., students' answers to multiple-choice and true/false questions associated with specific content, time spent to answer an question, and amount of scaffolding used) and, then, give an analysis of his/her problem-solving performance to each individual student (e.g., strengths and weaknesses). Based on the report, *SOLVEIT* will suggest either moving forward to the next problem with less scaffolding, repeating the same problem, or moving backward to the previous problems with more scaffolding. This function may enable instructors/researchers to observe the actual use of various types of scaffolding and measure its individual effect on students' skills and knowledge.

G. Post-assessments - students will take the same assessments at the end of *SOLVEIT*. Students will either complete *SOLVEIT*, practice problem solving more in *SOLVEIT*, or be given additional teaching materials relevant to problem solving.

Table 5.1 shows the six phases of the current version of *SOLVEIT* and future revision plans to the current *SOLVEIT* scaffolds in the phases. The suggested scaffolding revisions are grounded in the new framework.

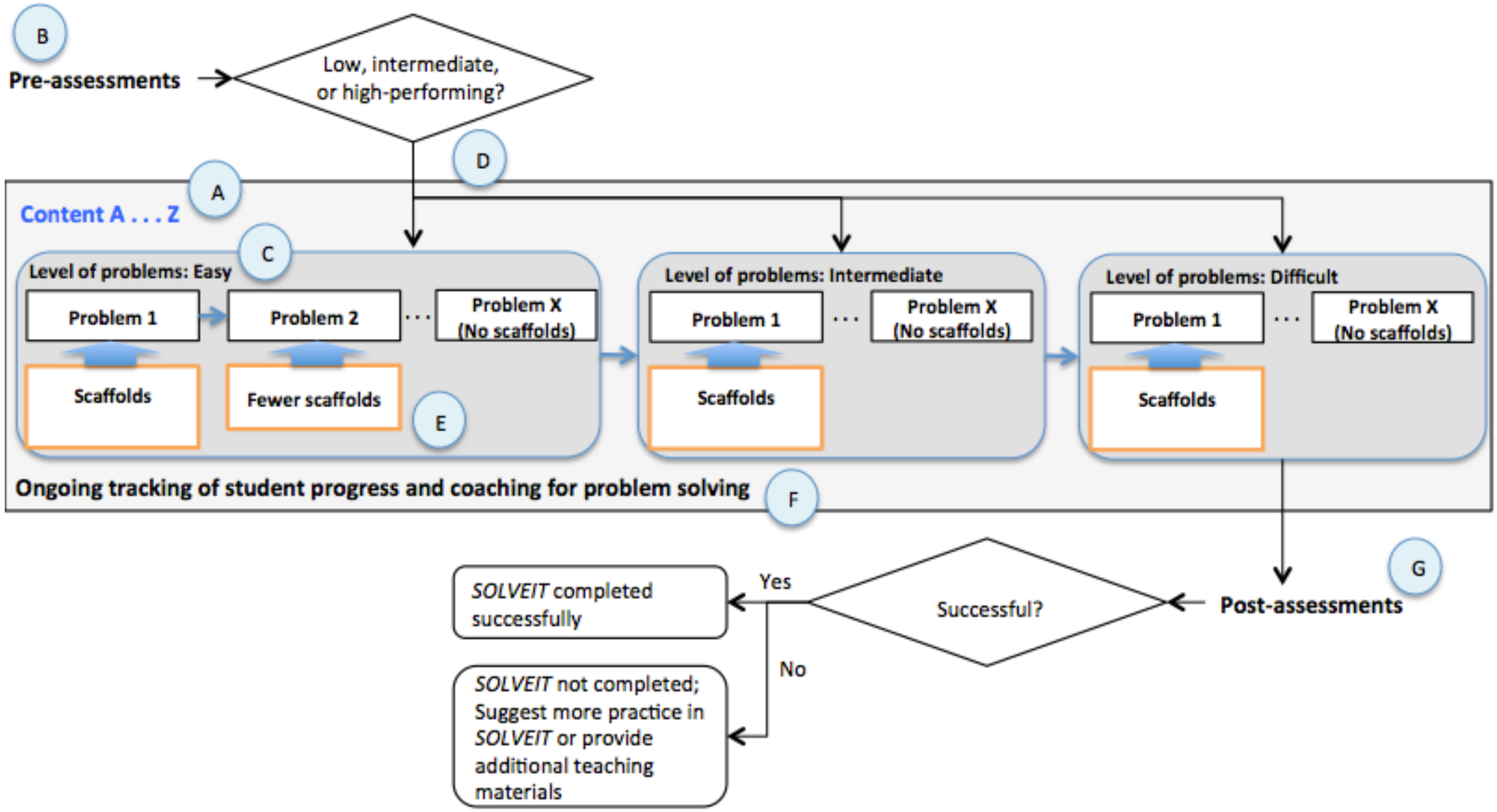

Figure 5.2. New adaptive *SOLVEIT* framework. (a) content - students/instructors choose content depending on their interests, (b) pre-assessments, (c) different difficulty levels of problems, which are well-structured complex science problems, (d) adaptive problem-solving path based on the results of pre-assessments, (e) multiple types of scaffolding, which is faded (f) ongoing tracking of student progress and coaching for problem solving, and (g) post-assessments

Table 5.1
Current scaffolds in SOLVEIT Phases and revisions to SOLVEIT scaffolds

SOLVEIT phases	Current *SOLVEIT* scaffolds	Future revision plans to the current *SOLVEIT* scaffolds grounded in the new framework
Phase 1 - Mandatory phase for recalling domain knowledge	• Prompts for students to express their understanding of important concepts in problems (two constructed-response questions) • Prompts such as "We've learned species concepts in class. Without using your notes, explain what species concepts are, and define each concept we discussed using your own words" • A focus on *self-explanation* effects • The same question prompts for all performance levels of students	• The re-design in this phase will depend on students' performance levels • High-performing students: this phase may be optional • Low-performing students: (a) this phase should be mandatory; (b) more specific question prompts about concepts should be provided; and (c) elaboration feedback for improving conceptual understanding may be provided after students enter their answers • There will be embedded support for students to manipulate relevant elements/parameters of scientific concepts or phenomena (e.g., simulation)
Phase 2 - Mandatory phase for building initial answers	• Prompts for students to express their initial understanding of the problem (one constructed-response question for each problem) • Prompts such as "Your answer should include a claim – a statement of whether the Island, Western, and Eastern Scrub Jays are the same or different species; evidence - an analysis of the data that supports your claim; and reasoning – a statement of how the evidence is connected to your claim based on different species concepts" • Support for students to focus on the structural features of the problem (e.g., the relations among the various data in the problem) rather than the surface features of it (e.g., a certain species)	• A message or an example will be embedded emphasizing the importance of understanding problem structure to actual problem-solving processes • There will be support for students to build their initial answers using different representation tools (e.g., maps, tables) • The re-design of this phase will depend on students' performance levels • High-performing students: this phase should be mandatory as representing understanding of the problem is important in science problem solving • Low-performing students: (a) this phase should be mandatory; (b) more specific question prompts should be provided for them to develop a coherent understanding of the problem (e.g., to clarify the most relevant factors and information related to the problem); (c) some prompts may be provided to elicit relevant prior knowledge; and (d) elaboration feedback may be provided after students enter their answers

	• A focus on *self-explanation* effects • The same question prompts for all performance levels of students	
Phase 3 - Mandatory phase for learning problem-solving steps	• Support for students to engage in important scientific problem-solving processes to reach the correct answers/solutions (step-by-step guidance with a number of multiple-choice questions and immediate elaboration feedback for each problem) • Prompts for students to (a) notice and correct misconceptions; (b) apply concepts to actual problems; (c) consider different assumptions; (d) engage in systematic data analysis; and (e) evaluate various conclusions • The same question prompts for all performance levels of students • Embedded visual guidance to show problem-solving steps • Additional interactive tutorials (optional) to teach important problem-solving skills (e.g., drawing conclusions based on data). If students respond incorrectly to particular questions, they are automatically linked to the interactive tutorials that address their error(s)	• Questions will prompt students to plan, monitor, and evaluate their problem-solving processes (constructed-response questions) • A summary (strengths and weaknesses) of students' problem-solving performance at the end of the process will be provided • *Fading of scaffolds*: the amount of scaffolding will be continuously reduced as students develop their skills • The re-design this phase depends on students' performance levels • High-performing students: this phase may be shorter (e.g., fewer question prompts and feedback) • Low-performing students: this phase may be longer (e.g., more question prompts and feedback) • Additional tutorials may be provided prior to Phase 1 to support students' development of fundamental problem-solving skills (e.g., analyzing data in tables and graphs)
Phase 4 - Mandatory phase for reflection	• Prompts for students to revise their initial answers • A focus on *self-explanation* effects • The same question prompts for all performance levels of students • A checklist students can refer to while they revise their initial answers (optional)	• A message or an example for emphasizing the importance of evaluation on solutions/answers will be embedded • Experts' answers may be provided after students enter their final answers (e.g., worked-out examples including explanations about why experts perform particular tasks in their problem solving.) • High-performing students: this phase should be mandatory as evaluating answers is important in science problem solving

		• Low-performing students: (a) this phase should be mandatory; (b) more specific question prompts should be provided for them to evaluate their answers with specific criteria; and (c) some question prompts may be added to encourage students to compare their answers with the experts' answers.
Phase 5 - Mandatory phase for metacognition	• Prompts for students to reflect on their thinking skills • Prompts such as "What are the important problem-solving skills you needed to solve Problem 1?" • A focus on *self-explanation* effects • The same question prompts for all performance levels of students	• This phase may be merged with Phase 3
Phase 6 - Optional phase for evaluating experts' models	• Review session: students can review Phase 1 through Phase 5 • Expert's answers	• This phase may be merged with Phase 4

Research Plan

Research Overview. The current *SOLVEIT* will be refined to make it more adaptive to students' levels of problem-solving skills. A multidisciplinary team consisting of researchers (faculty, post-doctoral students, graduate students) in the fields of Biochemistry and Molecular Biology, Learning Design and Technology, and Computer Science will be engaged in the revision process (see Figure 5.3):

- Creating content and problems in the domain of protein structure and function and metabolism (three protein structure function problems and three metabolism problems)
- Modifying and improving the current *SOLVEIT* interface (e.g., shortening the length of the six phases)
- Creating scaffolds for domain-specific problem solving
- Programming adaptive web-code (e.g., providing different problem-solving paths for students depending on the results of embedded assessments)
- Designing an administrator-friendly interface so that instructors can easily track students' progress in the program.

After completing the development of the major features of the adaptive *SOLVEIT*, the feasibility of the program will be evaluated with a biology instructor and a small number of students in an introductory biology course. The students will complete *SOLVEIT*. Then, students will respond to two different types of surveys about their experience with the program: (a) embedded pop-up survey questions while using *SOLVEIT* and (b) a comprehensive survey after completing the program. The short survey will consist of one embedded question at each important phase or feature of *SOLVEIT*. Short surveys will help us gauge the students' immediate opinions of *SOLVEIT's* interface, scaffolding and clarity of content while they are engaged in learning. Short surveys should be designed to cause only minimal disruption to the learning process in the program. In addition, the design team and the biology instructor will examine the content, the overall structure of *SOLVEIT* and the user-interface design to enhance the validity of the responses from the students. The instructor may request new content, suggest new problems, and make general comments and suggestions about the program.

According to the feedback from the participants in the feasibility test, appropriate revisions will be made to improve the program quality. Then, the complete version of the new adaptive *SOLVEIT* will be implemented to test the effectiveness of the program with a larger group of students in the same introductory biology course.

Objectives and tasks	2014	2015	2016	2017	2018
Creation of contents and problems in the domain of protein structure and metabolism provided in *SOLVEIT*					
Design of *SOLVEIT* layouts/pages/interfaces, scaffolding, and embedded assessments and surveys					
Development and continuous revision) Program/implement adaptive web-code (e.g., ongoing feedback)					
Feasibility testing of the program					
Implementation study (data collection and analysis)					
Hold onsite workshops about the use of *SOLVEIT* for college biology instructors					

Figure 5.3. SOLVEIT research plan

In the next section, I will discuss the research questions, hypotheses, and research design for the implementation studies. According to the results from the implementation studies, *SOLVEIT* will be refined, and we will disseminate the program for use in different biology education contexts.

Research Questions, Hypotheses, and Research Design. This study includes three main research questions and sub-questions for each main question about *SOLVEIT* and college students' problem-solving skills in biology. Hypotheses are formulated for each research question based on the findings from the prior *SOLVEIT* studies.

1. How do students use and evaluate the adaptive *SOLVEIT*? *Hypothesis 1.1.* Both high-performing and low-performing students will find the *SOLVEIT* problems and the multiple types of scaffolding appropriate and helpful for biology problem solving.

    a. How do high-performing and low-performing students use *SOLVEIT*?

    b. How do students solve the different levels of problems available in *SOLVEIT*?

    c. What difficulties do students experience with *SOLVEIT*?

    d. Do students believe that *SOLVEIT* provides appropriate support for the development and acquisition of conceptual understanding and problem-solving skills?

In order to determine the effect of the adaptive *SOLVEIT*, a comparison will be made between the *SOLVEIT* treatment section and a control section taught by the same instructor that did not provide *SOLVEIT* to students.

2. What is the impact of the adaptive *SOLVEIT* on students' science problem-solving skills? *Hypothesis 2.1.* Students in the treatment *SOLVEIT* section will demonstrate a more accurate understanding of the target concepts in the domains of protein structure and metabolism than participants in the comparison *SOLVEIT* section. *Hypothesis 2.2.* Students in the treatment section will use more successful problem-solving steps (e.g., correct analysis of scientific data, monitoring and checking of their problem-solving processes) than participants in the comparison section.

    a. What is the effect of *SOLVEIT* on high-performing and low-performing students' understanding of scientific concepts?

b. What is the effect of *SOLVEIT* on high-performing and low-performing students' solutions and problem-solving steps?

3. What is the influence of the adaptive *SOLVEIT* on students' motivation and confidence in solving biology problems? *Hypothesis 3.1.* Students in the treatment *SOLVEIT* section will show higher confidence in solving science problems as well as higher motivation to pursue science studies and professions than students in the comparison *SOLVEIT* section.

Conclusions

This dissertation may contribute to the educational research community by adding to the computer-based scaffolding knowledge base for college science learning. This study may also benefit college students by helping to develop their science problem-solving skills with appropriate scaffolding. However, scaffolding in the current version of *SOLVEIT* was tested only in an introductory biology course. In turn, *SOLVEIT* is limited in its potential for improving problem-solving skills in other disciplines as well as with other topics in biology. Through additional research studies identified above, I expect that the proposed computer-based scaffolding approach in *SOLVEIT* will be applicable to other biology courses (e.g., Cellular and Molecular Biology) and other science disciplines (e.g., Introductory Geology). Comprehensive subsequent research studies are required to achieve this outcome. As a result, it is my hope that through more widespread usage of *SOLVEIT* in college science classes, more college students may be prepared to solve science problems in a systematic way, become more willing to take on opportunities to resolve science problems in the real world, and be more likely to pursue science majors and professions.

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Appendices

Appendix A. Examples of the biology problems used for the pre-interview and post-interview

Snake Problem

32. You are interested in learning more about two snakes common to the Southeastern U.S. - the black rat snake and the gray rat snake traditionally recognized as members of a single species of rat snake *Elaphe obsoleta*. Currently scientists are debating whether these two snakes may actually be two different species. You have several pieces of data about the black rat snake and the gray rat snake (shown below). Consider the evidence and respond to the question on the next page. **(7 points)**

Table 1. Proportions of the black rat snake, the gray rat snake, and hybrid snakes found in traps*. For two different years, traps were set for snakes in a research plot at Southeast Botanical Gardens. The traps were regularly checked and the type of snake and the number of each type were determined. The relative proportion of each type for a single year is presented with the actual numbers counted in parentheses.*

Year	*Total*	*Black Rat Snake*	*Gray Rat Snake*	*Hybrids*
1	51	0.49 (25)	0.47 (24)	0.03 (2)
2	48	0.48 (23)	0.50 (24)	0.02 (1)

Table 2. Comparison of anatomical and behavioral features of black rat snakes, gray rat snakes, and hybrids.

Form:	*Black rat snake*	*Gray rat snake*	*Hybrids*
Average length	42-72 inches	Max length 101 inches	50-80 inches
Average width	1-3 inch diameter	3-5 inch diameter	2-4 inch diameter
Food and feeding	All are constrictors who eat small mammals, birds, and bird eggs.		

32. Are the black rat snake and the gray rate snack the same or different species? For your answer, state the following:
    - Your claim – same or different species? Cannot be determined?
    - Evidence for your claim including data from both Table 1 and Table 2.
    - Reasoning – why does the evidence support your claim, e.g., according to which species concept would your claim be valid? Be sure to define any species concept that you use in your answer.

Parasite Problem

In class we learned about *Plasmodium falciparum*, the parasite that causes malaria. *P. azurophilum* is a related parasite that causes malaria in *Anolis* lizards of the Caribbean. It is known that *P. azurophilum* can infect lizards' red blood cells and white blood cells. Scientists wanted to use various species concepts to understand whether *P. azurophilum* that infects red blood cells is the same or different species as *P. azurophilum* that infects white blood cells. They gathered the data below (modified from Perkins, S. 2000. *Proc R. Soc Lond*, 267, 2345-2350). Based on these data, are the *Plasmodium azurophilum* parasites that infect red blood cells the same or different species as the parasites that infect white blood cells? Consider the evidence and respond to the question below.

Table 1. Results from viewing *P. azurophilum* under a light microsope. *P. azurophilum* red is the type found in red blood cells; *P. azurophilum* white is the type found in white blood cells.

	P. azurophilum red	*P. azurophilum* white
Average parasite width	1.5 um $\pm$ .25 um	1.5 um $\pm$ .2 um
Average parasite length	4.26 um $\pm$ .17 um	4.27 um $\pm$ .19 um
Parasite shape	Round	Round

Table 2. Results from studies of hybridization between *P. azurophilum* red and *P. azurophilum* white.

	P. azurophilum red	*P. azurophilum* white
Observations based on parasites collected at different regions of the Caribbean	*P. azurophilum* red and white are reproductively isolated. No evidence of hybridization could be found.	
Experimental attempts to hybridize	Unable to successfully hybridize *P. azurophilum* red with *P. azurophilum* white.	

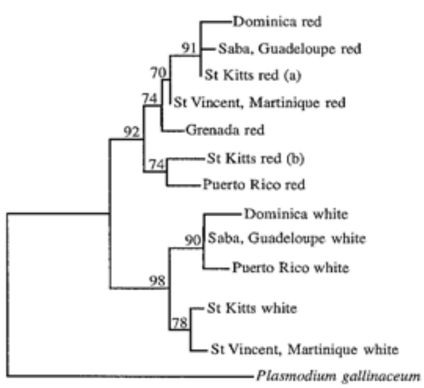


Figure 1. Evolutionary tree based on genetic analysis of *P. azurophilum* parasites collected from various Caribbean islands (e.g., Dominica, Saba, St. Kitts, etc.). "Red" indicates parasites that infect red blood cells. "White" indicates parasites that infect white blood cells. The numbers indicate the statistical strength of each node with any number greater than 70 providing strong statistical support.

Are the *P. azurophilum* red and *P. azurophilum* white parasites the same or different species? For your answer, state the following:

- Your claim – same or different species? Cannot be determined?
- Evidence for your claim including data Table 1, Table 2, and Figure 1.
- Reasoning – why does the evidence support your claim, e.g., according to which species concept would your claim be valid? Be sure to define any species concept that you use in your answer.

Toad problem

42. Recall the toad question from class where your group discovered a previously unidentified toad on Santa Cruz Island off the coast of California. You named this toad the Island Toad. The range of the Island Toad, Western Toad and the Eastern Toad are shown on the map below. Suppose your group makes the hypothesis that the Island, Western, and Eastern Toads are all different species and you gather the data below. Given these data, what conclusion can you make about the whether the Island, Western, and Eastern Toads are the same or different species? Your answer should include (1) your claim that states whether the Island, Western, and Eastern Toads are the same or different species (a sentence), (2) an analysis of the results that support your claim (several pieces of evidence) and a description of any species concepts referenced to analyze the results and (3) an explanation of why the results support your claim.

Figure 1. U.S. and Santa Cruz Island showing the range of the Island, Western, and Eastern Toads.

Table 1. Comparison of anatomy, habitat and feeding of Island, Western, and Eastern Toads.

Form	**Island Toad**	**Western Toad**	**Eastern Toad**
Average snout length	2.4-2.8 mm	2.5-2.7 mm	2.3-2.7 mm
Average body length	15-18 mm	16-17 mm	14-18 mm
Coloration	Yellow and black	Brown	Brown
Habitat	Semi-terrestrial	Semi-terrestrial	Semi-terrestrial
Food and feeding	Flies, mosquitoes, dragonflies	Flies, mosquitoes, dragonflies	Flies, mosquitoes, dragonflies

Table 2. Proportions of the Western and Eastern Toads found in traps in Oklahoma. For two different years, traps were set for toads in a research plot at Oklahoma Botanical Gardens. The traps were regularly checked and the type of Toad and the number of each type were determined. The relative proportion of each type for a single year is presented with the actual numbers counted in parentheses.

Year	**Total**	**Western Toads**	**Eastern Toads**	**Western/Eastern Hybrid Toads**
1	51	0.49 (25)	0.47 (24)	0.03 (2)
2	48	0.48 (23)	0.50 (24)	0.02 (1)

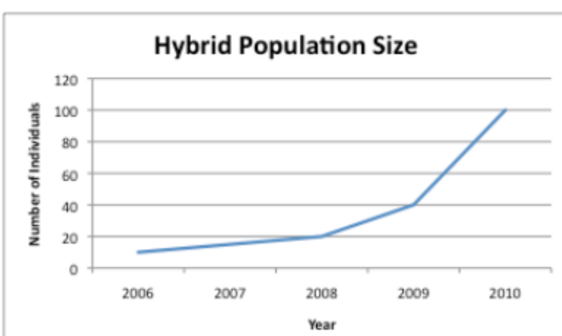


Figure 2. Data from a breeding and reintroduction experiment with Island and Western Toads. Island/Western Toad hybrids were obtained by breeding the Island and Western Toads in captivity. Hybrids were introduced to a small forest in Kansas lacking a native Toad population. The hybrid population size from the year of introduction (2006) to 2010 is shown.

Appendix B. Rubric to score students' constructed-responses from the pretest and posttest

Claim:

0	Does not provide a claim or provides an inaccurate claim
1	Provides an accurate and complete claim.

Evidence:

0	Does not provide evidence or only inappropriate evidence.
1	Provides one piece of appropriate evidence; may include some inappropriate evidence.
2	Provides two or more pieces of appropriate evidence; may include some inappropriate evidence.
3	Provides two or more pieces of sufficient and appropriate evidence and no inappropriate evidence.

Reasoning:

0	Does *not* provide reasoning that links evidence to the claim *and* lacks appropriate scientific principles.
1	Provides reasoning that link the claim and evidence by repeating the evidence; lacks sufficient explanation and scientific principles; may include some inappropriate principles.
2	Provides reasoning that link the claim and evidence, and includes some appropriate scientific principles but not sufficient; may include a few inappropriate principles.
3	Provides reasoning that links evidence to claim, includes appropriate and sufficient scientific principles.

Appendix C. The Test of Scientific Literacy Skills (TOSLS)

Directions: There are 28 multiple-choice questions. You will have about 35 minutes to work on the questions. Be sure to answer as many of the questions as you can in the time allotted. You will receive attendance points for completing the entire assignment today. Your grade will depend on completeness and thoroughness, not on correct answers. But, try your best, your honest answers will help us better prepare the materials for the remainder of the semester.

Mark your answers on the scantron sheet.

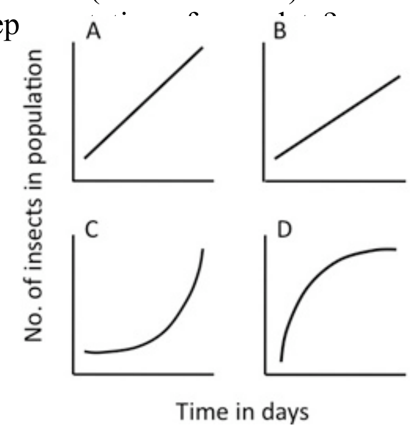
Bubble in your #ID on your scantron.

Do NOT use a calculator. Thank you for your participation in this project!

11. Which of the following is a valid scientific argument?
    a. Measurements of sea level on the Gulf Coast taken this year are lower than normal; the average monthly measurements were almost 0.1 cm lower than normal in some areas. These facts prove that sea level rise is not a problem.
    b. A strain of mice was genetically engineered to lack a certain gene, and the mice were unable to reproduce. Introduction of the gene back into the mutant mice restored their ability to reproduce. These facts indicate that the gene is essential for mouse reproduction.
    c. A poll revealed that 34% of Americans believe that dinosaurs and early humans co-existed because fossil footprints of each species were found in the same location. This widespread belief is appropriate evidence to support the claim that humans did not evolve from ape ancestors.
    d. This winter, the northeastern US received record amounts of snowfall, and the average monthly temperatures were more than 2°F lower than normal in some areas. These facts indicate that climate change is occurring.

12. While growing vegetables in your backyard, you noticed a particular kind of insect eating your plants. You took a rough count (see data below) of the insect population over time. Which graph shows the best rep

Time (days)	Insect Population (number)
2	7
4	16
8	60
10	123



13. A study about life expectancy was conducted using a random sample of 1,000 participants from the United States. In this sample, the average life expectancy was 80.1 years for females and 74.9 years for males. What is one way that you can **increase your certainty** that women truly live longer than men in the United States' general population?
    a. Subtract the average male life expectancy from the average female expectancy. If the value is positive, females live longer.
    b. Conduct a statistical analysis to determine if females live significantly longer than males.
    c. Graph the mean (average) life expectancy values of females and males and visually analyze the data.
    d. There is no way to increase your certainty that there is a difference between sexes.

14. Which of the following research studies is **least likely** to contain a confounding factor (variable that provides an alternative explanation for results) in its design?
    a. Researchers randomly assign participants to experimental and control groups. Females make up 35% of the experimental group and 75% of the control group.
    b. To explore trends in the spiritual/religious beliefs of students attending U.S. universities, researchers survey a random selection of 500 freshmen at a small private university in the South.
    c. To evaluate the effect of a new diet program, researchers compare weight loss between participants randomly assigned to treatment (diet) and control (no diet) groups, while controlling for average daily exercise and pre-diet weight.
    d. Researchers tested the effectiveness of a new tree fertilizer on 10,000 saplings. Saplings in the control group (no fertilizer) were tested in the fall, whereas the treatment group (fertilizer) were tested the following spring.

15. Which of the following actions is a valid scientific course of action?
    a. A government agency relies heavily on two industry-funded studies in declaring a chemical found in plastics safe for humans, while ignoring studies linking the chemical with adverse health effects.
    b. Journalists give equal credibility to both sides of a scientific story, even though one side has been disproven by many experiments.
    c. A government agency decides to alter public health messages about breast-feeding in response to pressure from a council of businesses involved in manufacturing infant formula.
    d. Several research studies have found a new drug to be effective for treating the symptoms of autism; however, a government agency refuses to approve the drug until long term effects are known.

Background for question 16: The following graph appeared in a scientific article[4] about the effects of pesticides on tadpoles in their natural environment.

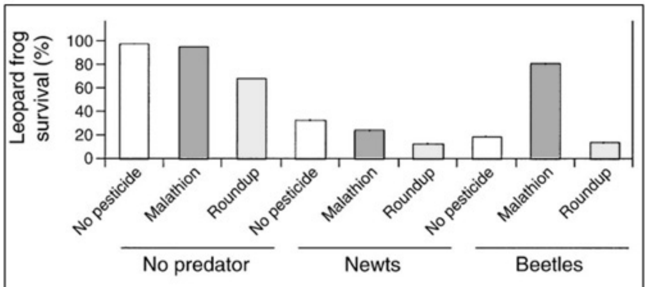
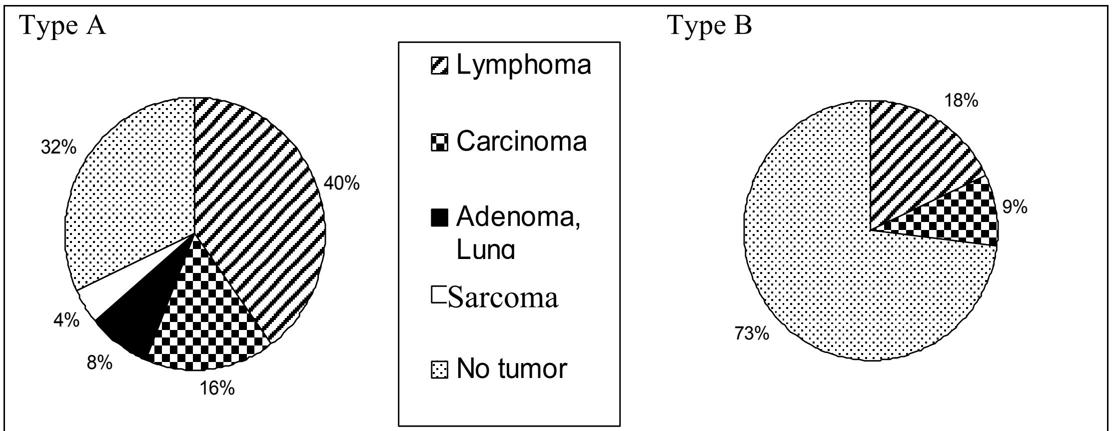


Fig. 2. Total survival of Leopard frog tadpoles living in ponds with 2 pesticides added (Malathion and Roundup) and 2 tadpole predators present (newts and beetles).

16. When beetles were introduced as predators to the Leopard frog tadpoles, and the pesticide Malathion was added, the results were unusual. Which of the following is a plausible hypothesis to explain these results?
    a. The Malathion killed the tadpoles, causing the beetles to be hungrier and eat more tadpoles.
    b. The Malathion killed the tadpoles, so the beetles had more food and their population increased.
    c. The Malathion killed the beetles, causing fewer tadpoles to be eaten.
    d. The Malathion killed the beetles, causing the tadpole population to prey on each other.

17. Which of the following is the **best** interpretation of the graph below[5]?



Tumors found in type A and type B mice. Pie chart depicts relative incidence of tumors. Numbers outside each slice denote the percentage of specific tumor type.

a. Type "A" mice with Lymphoma were more common than type "A" mice with no tumors.
b. Type "B" mice were more likely to have tumors than type "A" mice.
c. Lymphoma was equally common among type "A" and type "B" mice.
d. Carcinoma was less common than Lymphoma only in type "B" mice.

[4] Modified from Relyea, R.A., N.M. Schoeppner, J.T. Hoverman. 2005. Pesticides and amphibians: the importance of community context. Ecological Applications 15: 1125-1134

[5] Modified from Wang, Y., S. Klumpp, H.M. Amin, H. Liang, J. Li, Z. Estrov, P. Zweidler-McKay, S.J.Brandt, A. Agulnick, L. Nagarajan. 2010. SSBP2 is an *in vivo* tumor suppressor and regulator of LDB1 stability. Oncogene 29: 3044-3053.

18. Creators of the Shake Weight, a moving dumbbell, claim that their product can produce "incredible strength!" Which of the additional information below would provide the **strongest evidence** supporting the effectiveness of the Shake Weight for increasing muscle strength?
    a. Survey data indicates that on average, users of the Shake Weight report working out with the product 6 days per week, whereas users of standard dumbbells report working out 3 days per week.
    b. Compared to a resting state, users of the Shake Weight had a 300% increase in blood flow to their muscles when using the product.
    c. Survey data indicates that users of the Shake Weight reported significantly greater muscle tone compared to users of standard dumbbells.
    d. Compared to users of standard dumbbells, users of the Shake Weight were able to lift weights that were significantly heavier at the end of an 8-week trial.

19. Which of the following is **not** an example of an appropriate use of science?
    a. A group of scientists who were asked to review grant proposals based their funding recommendations on the researcher's experience, project plans, and preliminary data from the research proposals submitted.
    b. Scientists are selected to help conduct a government-sponsored research study on global climate change based on their political beliefs.
    c. The Fish & Wildlife Service reviews its list of protected and endangered species in response to new research findings.
    d. The Senate stops funding a widely used sex-education program after studies show limited effectiveness of the program.

Background for question 20: Your interest is piqued by a story about human pheromones on the news. A Google search leads you to the following website:

20. For this website (Eros Foundation), which of the following characteristics is **most important** in your confidence that the resource is accurate or not.
   a. The resource may not be accurate, because appropriate references are not provided.
   b. The resource may not be accurate, because the purpose of the site is to advertise a product.
   c. The resource is likely accurate, because appropriate references are provided.
   d. The resource is likely accurate, because the website's author is reputable.

Background for questions 21 – 24: Use the excerpt below (modified from a recent news report on MSNBC.com) for the next few questions.

"A recent study, following more than 2,500 New Yorkers for 9+ years, found that people who drank diet soda every day had a 61% higher risk of vascular events, including stroke and heart attack, compared to those who avoided diet drinks. For this study, Hannah Gardner's research team randomly surveyed 2,564 New Yorkers about their eating behaviors, exercise habits, as well as cigarette and alcohol consumption. Participants were also given physical check-ups, including blood pressure measurements and blood tests for cholesterol and other factors that might affect the risk for heart attack and stroke. The increased likelihood of vascular events remained even after Gardener and her colleagues accounted for risk factors, such as smoking, high blood pressure and high cholesterol levels. The researchers found no increased risk among people who drank regular soda."

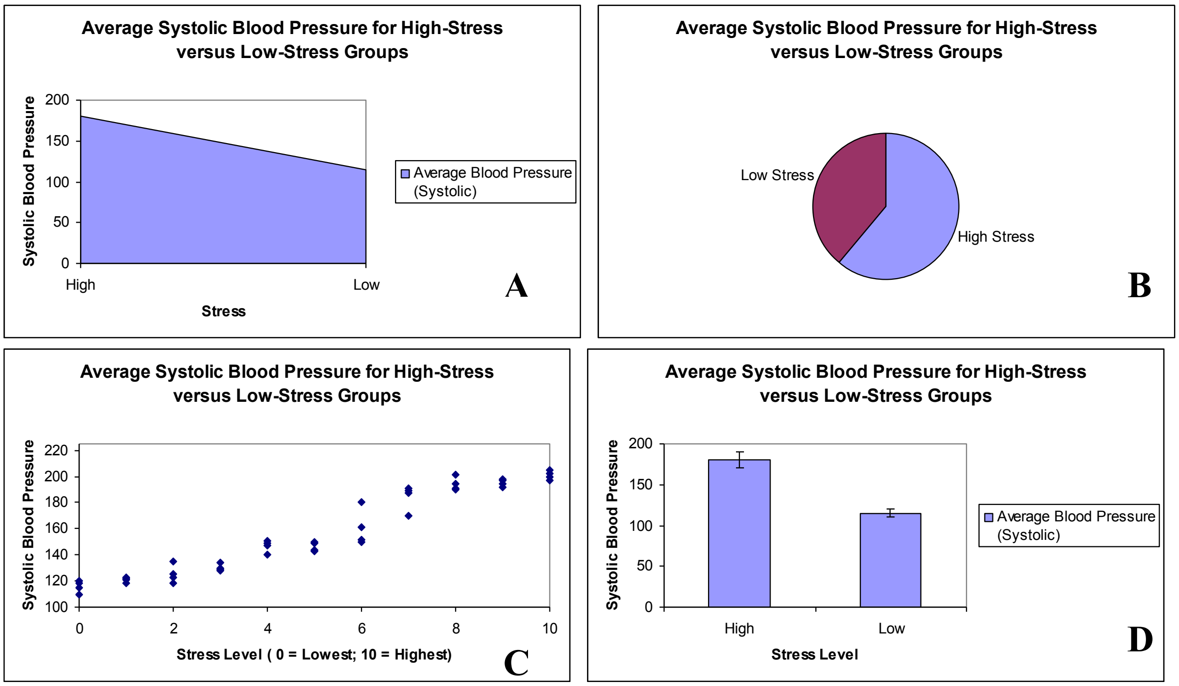
21. The findings of this study suggest that consuming diet soda might lead to increased risk for heart attacks and strokes. From the statements below, identify **additional evidence that supports** this claim:
    a. Findings from an epidemiological study suggest that NYC residents are 6.8 times more likely to die of vascular-related diseases compared to people living in other U.S. cities.
    b. Results from an experimental study demonstrated that individuals randomly assigned to consume one diet soda each day were twice as likely to have a stroke compared to those assigned to drink one regular soda each day.
    c. Animal studies suggest a link between vascular disease and consumption of caramel-containing products (ingredient that gives sodas their dark color).
    d. Survey results indicate that people who drink one or more diet soda each day smoke more frequently than people who drink no diet soda, leading to increases in vascular events.

22. The excerpt above comes from what type of source of information?
    a. Primary (Research studies performed, written and then submitted for peer-review to a scientific journal.)
    b. Secondary (Reviews of several research studies written up as a summary article with references that are submitted to a scientific journal.)
    c. Tertiary (Media reports, encyclopedia entries or documents published by government agencies.)
    d. None of the above

23. The lead researcher was quoted as saying, "I think diet soda drinkers need to stay tuned, but I don't think that anyone should change their behaviors quite yet." Why didn't she warn people to stop drinking diet soda right away?
    a. The results should be replicated with a sample more representative of the U.S. population.
    b. There may be significant confounds present (alternative explanations for the relationship between diet sodas and vascular disease).
    c. Subjects were not randomly assigned to treatment and control groups.
    d. All of the above

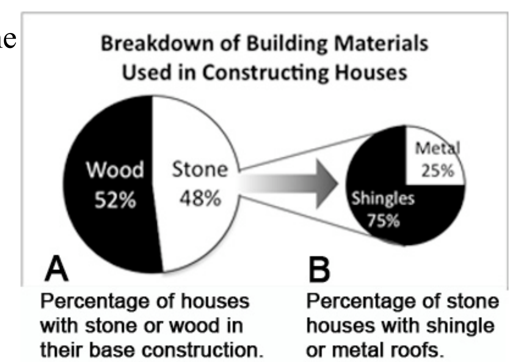
24. Which of the following attributes is **not** a strength of the study's research design?"
    a. Collecting data from a large sample size.
    b. Randomly sampling NYC residents.
    c. Randomly assigning participants to control and experimental groups.
    d. All of the above.

25. Researchers found that chronically stressed individuals have significantly higher blood pressure compared to individuals with little stress. Which graph would be most appropriate for displaying the mean (average) blood pressure scores for high-stress and low-stress groups of people?



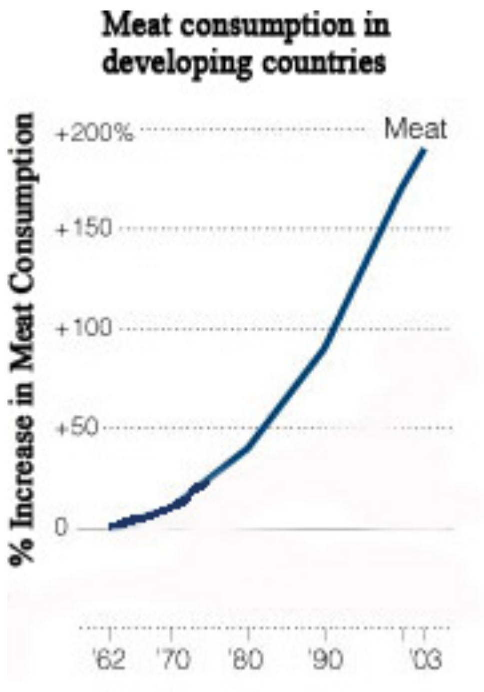
<u>Background for question 25:</u> Energy efficiency of houses depends on the construction materials used and how they are suited to different climates. Data was collected about the types of building materials used in house construction (results shown below). Stone houses are more energy efficient, but to determine if that efficiency depends on roof style, data was also collected on the percentage of stone houses that had either shingles or a metal roof.

26. What proportion of houses were constructed of a stone base with a shingled roof?
    a. 25%
    b. 36%
    c. 48%
    d. Cannot be calculated without knowing the original number of survey participants.



27. The **<u>most important</u>** factor influencing you to categorize a research article as trustworthy science is:
    a. the presence of data or graphs
    b. the article was evaluated by unbiased third-party experts
    c. the reputation of the researchers
    d. the publisher of the article

28. Which of the following is the **most accurate** conclusion you can make from the data in this graph[6]?



a. The largest increase in meat consumption has occurred in the past 20 years.
b. Meat consumption has increased at a constant rate over the past 40 years.
c. Meat consumption doubles in developing countries every 20 years.
d. Meat consumption increases by 50% every 10 years.

29. Two studies estimate the mean caffeine content of an energy drink. Each study uses the same test on a random sample of the energy drink. Study 1 uses 25 bottles, and study 2 uses 100 bottles. Which statement is true?

a. The estimate of the actual mean caffeine content from each study will be equally uncertain.
b. The uncertainty in the estimate of the actual mean caffeine content will be smaller in study 1 than in study 2.
c. The uncertainty in the estimate of the actual mean caffeine content will be larger in study 1 than in study 2.
d. None of the above

30. A hurricane wiped out 40% of the wild rats in a coastal city. Then, a disease spread through stagnant water killing 20% of the rats that survived the hurricane. What percentage of the original population of rats is left after these 2 events?

a. 40%
b. 48%
c. 60%
d. Cannot be calculated without knowing the original number of rats.

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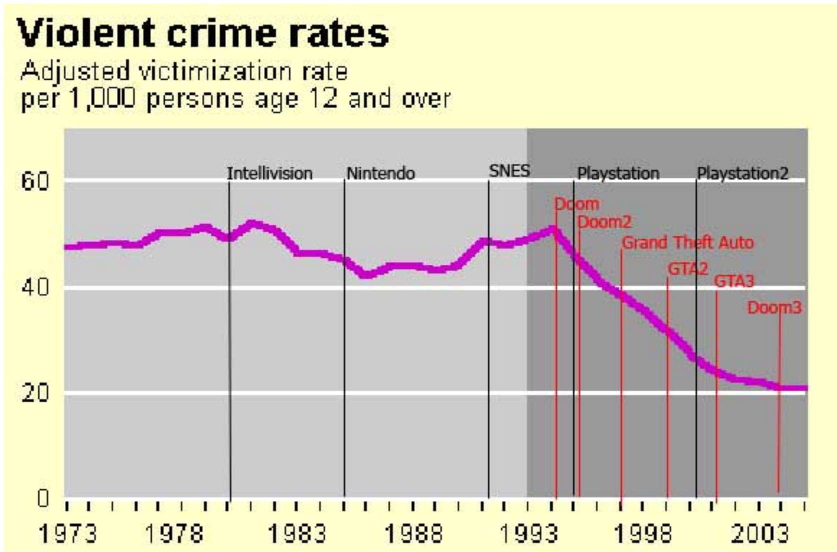
[6] Modified from Rosenthal, Elizabeth. 2008. As More Eat Meat, a Bid to Cut Emissions. New York Times, December 3, 2008. Accessed June 9, 2011 http://www.nytimes.com/2008/12/04/science/earth/04meat.html

<u>Background for question 31:</u> A videogame enthusiast argued that playing violent video games (e.g., Doom, Grand Theft Auto) does not cause increases in violent crimes as critics often claim. To support his argument, he presents the graph below. He points out that the rate of violent crimes has decreased dramatically, beginning around the time the first "moderately violent" video game, Doom, was introduced.



31. Considering the information presented in this graph, what is the **<u>most critical flaw</u>** in the blogger's argument?
    a. Violent crime rates appear to increase slightly after the introduction of the Intellivision and SNES game systems.
    b. The graph does not show violent crime rates for children under the age of 12, so results are biased.
    c. The decreasing trend in violent crime rates may be caused by something other than violent video games
    d. The graph only shows data up to 2003. More current data are needed.

32. Your doctor prescribed you a drug that is brand new. The drug has some significant side effects, so you do some research to determine the effectiveness of the new drug compared to similar drugs on the market. Which of the following sources would provide the **<u>most accurate</u>** information?
    a. the drug manufacturer's pamphlet/website
    b. a special feature about the drug on the nightly news
    c. a research study conducted by outside researchers
    d. information from a trusted friend who has been taking the drug for six months

33. A gene test shows promising results in providing early detection for colon cancer. However, 5% of all test results are falsely positive; that is, results indicate that cancer is present when the patient is, in fact, cancer-free. Given this false positive rate, how many people out of 10,000 would have a false positive result and be alarmed unnecessarily?
    a. 5
    b. 35
    c. 50
    d. 500

34. Why do researchers use statistics to draw conclusions about their data?
    a. Researchers usually collect data (information) about everyone/everything in the population.
    b. The public is easily persuaded by numbers and statistics.
    c. The true answers to researchers' questions can only be revealed through statistical analyses.
    d. Researchers are making inferences about a population using estimates from a smaller sample.

35. A researcher hypothesizes that immunizations containing traces of mercury **do not** cause autism in children. Which of the following data provides the **strongest** test of this hypothesis?
    a. a count of the number of children who were immunized and have autism
    b. yearly screening data on autism symptoms for immunized and non-immunized children from birth to age 12
    c. mean (average) rate of autism for children born in the United States
    d. mean (average) blood mercury concentration in children with autism

Background for Question 36: You've been doing research to help your grandmother understand two new drugs for osteoporosis. One publication, *Eurasian Journal of Bone and Joint Medicine*, contains articles with data only showing the effectiveness of one of these new drugs. A pharmaceutical company funded the *Eurasian Journal of Bone and Joint Medicine* production and most advertisements in the journal are for this company's products. In your searches, you find other articles that show the same drug has only limited effectiveness.

36. Pick the **best** answer that would help you decide about the credibility of the *Eurasian Journal of Bone and Joint Medicine*:
    a. It is not a credible source of scientific research because there were advertisements within the journal.
    b. It is a credible source of scientific research because the publication lists reviewers with appropriate credentials who evaluated the quality of the research articles prior to publication.
    c. It is not a credible source of scientific research because only studies showing the effectiveness of the company's drugs were included in the journal.
    d. It is a credible source of scientific research because the studies published in the journal were later replicated by other researchers.

37. Which of the following actions is a valid scientific course of action?

a. A scientific journal rejects a study because the results provide evidence against a widely accepted model.
b. The scientific journal, Science, retracts a published article after discovering that the researcher misrepresented the data.
c. A researcher distributes free samples of a new drug that she is developing to patients in need.
d. A senior scientist encourages his graduate student to publish a study containing ground-breaking findings that cannot be verified.

<u>Background for question 38:</u> Researchers interested in the relation between River Shrimp (Macrobrachium) abundance and pool site elevation, presented the data in the graph below. Interestingly, the researchers also noted that water pools tended to be shallower at higher elevations.

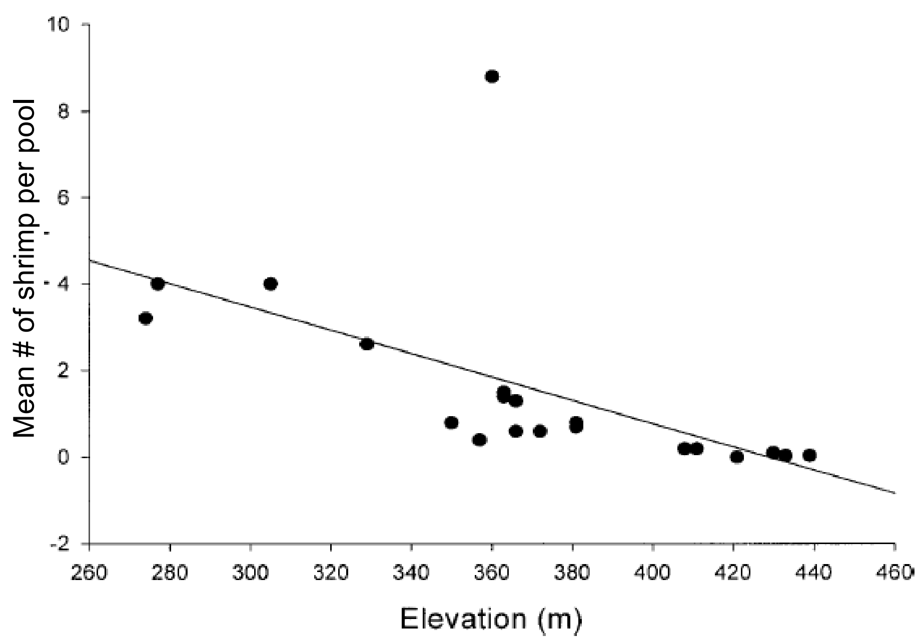


FIG. 3. Relationship between total abundance of *Macrobrachium* (1988–2002) and elevation in Quebrada Prieta.

38. Which of the following is a plausible hypothesis to explain the results presented in the graph?

a. There are more water pools at elevations above 340 meters because it rains more frequently in higher elevations.
b. River shrimp are more abundant in lower elevations because pools at these sites tend to be deeper.
c. This graph cannot be interpreted due to an outlying data point.
d. As elevation increases, shrimp abundance increases because they have fewer predators at higher elevations.