Physiology and the Biomedical Engineering Curriculum: Utilizing emerging instructional technologies to promote development of adaptive expertise in undergraduate students

By

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ABSTRACT

A mixed-methods research study was designed to test whether undergraduate engineering students were better prepared to learn advanced topics in biomedical engineering if they learned physiology via a quantitative, concept-based approach rather than a qualitative, system-based approach. Experiments were conducted with undergraduate engineering student participants and the resultant quantitative and qualitative data were evaluated. This dissertation presents three contributions that have been made to the field of biomedical engineering education: a curriculum contribution, an applied pedagogical contribution and a theory-testing contribution. The curriculum contribution focuses on the physiology sub-curriculum of undergraduate biomedical engineering programs and describes a process by which physiology courses structured around organ systems can be converted to courses that focus on core physiology concepts. An applied pedagogical or teaching contribution is made through the observation of interaction in spaces used for collaborative problem-solving in an online undergraduate learning environment. An online discussion forum, avatar-based chat in a multi-user virtual environment and a wiki are evaluated in this study. Finally, the theory-testing contribution utilizes qualitative research methods to analyze data from the learning records of study participants for evidence of adaptive expertise. A multiple case study comparison of participants with low, mid and high scores on the Index of Adaptive Expertise is reported.

Chapter 1 - Introduction

This research explored the physiology education component or "physiology sub-curriculum" of undergraduate biomedical engineering (BME) curricula in programs accredited by ABET, Inc (formerly, the Accreditation Board for Engineering and Technology). The specific objectives of this study were to:

- Review and describe the content and structure of the physiology sub-curricula in ABET-accredited undergraduate biomedical engineering programs to provide a "snapshot" of the current state of physiology within BME programs
- Develop aspects of a model physiology sub-curriculum that could be implemented in BME undergraduate programs
- Explore the implementation of collaborative challenge-based learning in an online learning environment
- Test the hypotheses that the mathematical approach to physiology instruction (Quantitative vs. Qualitative) and the way the content is structured (Concept-based vs. System-based) affect how engineering students transfer physiology knowledge and skills to learn biomedical engineering topics in subsequent courses
- Explore how undergraduate engineering students demonstrate adaptive expertise when learning new engineering topics.

1.1 Dissertation Overview

Chapter 1 presents a background and overview that provides a conceptual framework for this dissertation of the research problem before the research problems are stated. Related literature is presented in Chapter 2. The development and presentation of a process for converting physiology lessons structured around organ systems to lessons structured around physiology and engineering concepts is described in Chapter 3. The next chapter describes the development of the instrumentation and testing protocol for the research experiment. An analysis of collaborative problem-solving spaces in online learning environments and suggestions for instructor facilitation of student collaboration in these spaces is presented in Chapter 5. This chapter is followed by the statistical analysis of the quantitative experiment. Chapter 7 reports a comparative case study of undergraduate engineering students with high and low adaptive expertise scores. Finally, conclusions, implications and suggestions for future research are presented in Chapter 8.

1.2 Background of the Problem

Biomedical engineering as an academic discipline advanced considerably in the latter half of the 20th century. decade. The first university training programs in biomedical engineering appeared in the 1950s, about the same time that professional societies in the discipline began to emerge. By 1965, 40 universities had BME programs and by 1980, there were about 100 programs or departments in biomedical engineering. Many universities first offered only graduate degrees to students who came from various undergraduate engineering disciplines. In 2013, approximately 80 ABET-accredited programs granted four-year undergraduate degrees in biomedical engineering.

The ABET accreditation criteria specifically include biomedical engineering and bioengineering programs that are not involved with agriculture. Agriculture-based engineering programs fall under the auspices of biological engineering, another ABET accreditation class (Accreditation Board for Engineering and Technology, 2013). Biomedical engineering programs must meet ABET criteria related to physiology. The specific requirement states that “the program must demonstrate that graduates have: an understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology as well as the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems.”

ABET-accredited programs meet these criteria in different ways. An evaluation of overall curricula in BME programs shows a common core of coursework for undergraduates in ABET-accredited programs exists to some extent, but this core is not universally required (Linsenmeier & Gatchell, 2006). At least 70% of the programs evaluated require courses in physiology, biology, mechanics, circuit analysis, computing, materials science, design, transport phenomena, instrumentation and statistics. Functionally, these courses have been considered the core of the biomedical engineering curriculum. These data were obtained through surveys conducted by the Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center for Bioengineering Educational Technologies [hereafter referred to as VaNTH] through their Bioengineering Core Curriculum project.

The Core Curriculum Project looked closely at the physiology sub-curriculum. The researchers at VaNTH found that developing a core physiology curriculum was a formidable task. An early plan to develop a comprehensive curriculum of physiology for biomedical engineers as an encyclopedic taxonomy was aborted. Next, the VaNTH team launched a physiology taxonomy project that aimed to provide a detailed topical outline of the physiology systems with links to taxonomies in other bioengineering domains that were being developed concurrently. This project also proved to be impractical given available resources and a lack of consensus among the research team (Troy & Linsenmeier, 2003). VaNTH was able to develop a system-based physiology taxonomy that reflected the topics covered in physiology courses in ABET accredited programs (see Appendix A). This system-based physiology taxonomy is extensive. Individual programs will likely make different content decisions since presenting all of the topics in one or two courses would be difficult.

BME programs utilize different approaches and strategies to satisfy the ABET criteria and present physiology content to their undergraduate students. A 2012 review of undergraduate curriculum requirements in ABET-accredited programs found that a required physiology course was offered by the biomedical engineering department in 49% of the programs. Forty-one percent of the BME programs utilized life science departments at the university to teach physiology courses to their BME students. One BME program had required courses in physiology from both the BME and Biology departments, while 8% of the undergraduate programs had no required course in physiology at all. The number of required credit hours in physiology in the other programs ranged from three to twelve credits over the course of the undergraduate curriculum (see Figure 1-1). Although only five of the programs had physiology courses that listed calculus, differential equations or engineering mathematics as a prerequisite, the recommended semester for taking the first physiology course was after the recommended semester for Calculus II in 98% of the programs (see Appendix B for full results). As such, BME students should be able to use some higher level mathematical concepts when learning physiology.

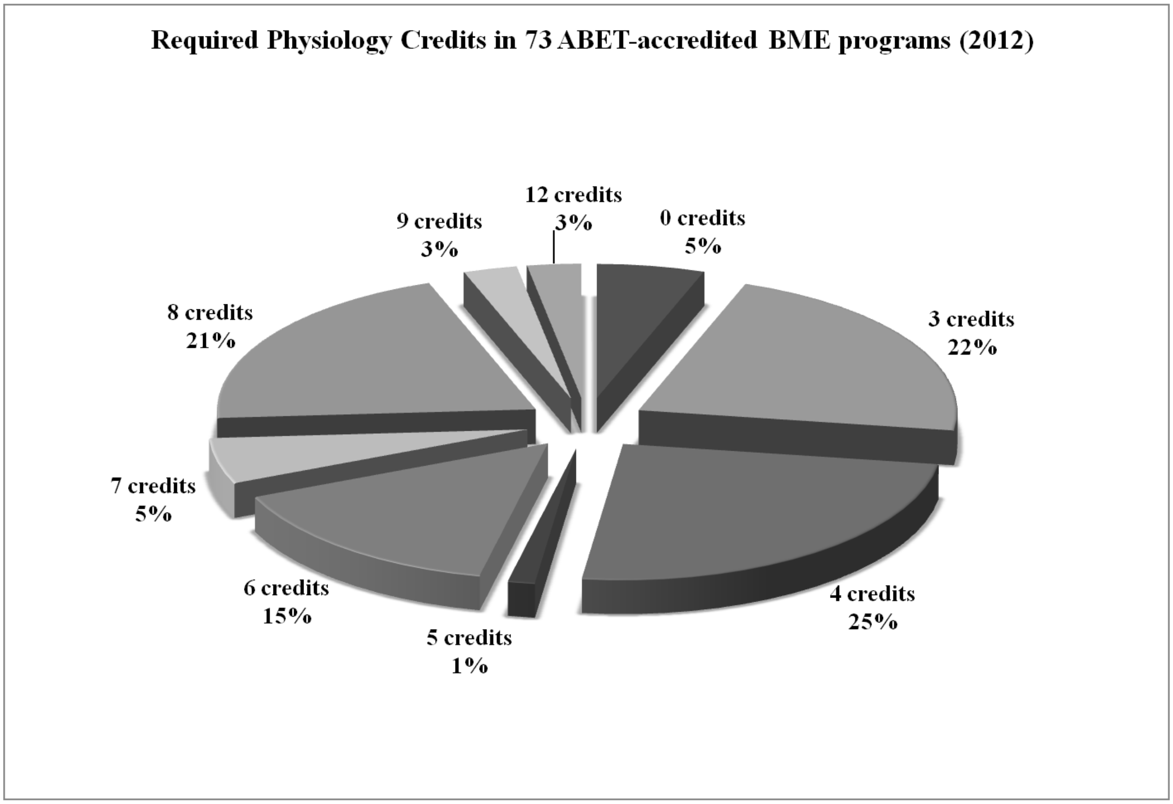

Figure 1-1. Number of physiology credits required by ABET-accredited undergraduate programs in biomedical engineering from a 2012 review of core curricula (see Appendix B for additional detail)

1.3 Statement of the Problem

The content of physiology courses for biomedical engineering undergraduates in the United States varies from program to program. In 2012, just about half of ABET-accredited undergraduate BME programs offered physiology courses through the engineering department. In other programs, students were required to take courses offered by the bioscience, biology, physiology, zoology or biological sciences departments. These non-engineering courses tend to be qualitative in nature, requiring minimal mathematics background and skills on the part of the students. Physiology courses taught by engineering departments most often have a quantitative slant and require students be able to use calculus and differential equations in problem-solving.

In general, the mathematical approach to teaching physiology courses to biomedical engineers falls at different points along a qualitative – quantitative continuum.

Physiology courses for biomedical engineers can also differ in how the course content is structured along a system-based – concept-based continuum. In most cases, physiology content is structured around human organ systems (e.g., cardiovascular, neuromuscular, respiratory) exploring one system thoroughly before moving to the next. An alternative approach is to structure the course around concepts (e.g., homeostasis, bioelectricity) and explore physiology systems as they relate to these concepts.

VaNTH initially created a concept-based physiology taxonomy by considering content and skills that lead to success in biomedical engineering. This taxonomy emphasized unifying themes and principles that occur in physiology systems:

- homeostasis and control systems
- communication and coordination
- structure/function relationships
- levels of organization in the body
- compartmentation
- bioelectricity
- biological energy
- movement and associated forces (molecular to biomechanics)
- biological transduction (molecular and sensory)
- heat balance
- mass balance
- mass flow (transport)
- emergent properties of complex systems
- scaling in biological systems
- physiological variables
- biological units of measure (Silverthorn, 2002; VaNTH, 2007a).

The pedagogy behind the concept-based approach is that if students are well grounded in the key concepts they will be able to generalize this knowledge as they learn about new physiology systems, promoting self-learning and development of adaptive expertise (Troy &

Linsenmeier, 2003). Adaptive expertise has also been assessed as a linear transformation of learning gains in factual knowledge and conceptual knowledge, as well as transfer of learning using the Index of Adaptive Expertise (Pandy, 2004).

Another concept-based taxonomy that may have relevance for biomedical engineering focuses on physiology principles as opposed to physiology topics (Feder, 2005). This framework focused on thirteen defining principles presented from a physiologist's perspective that should be part of every undergraduate course in physiology:

1. Evolution has resulted in organisms comprising mechanisms for maintenance, growth, and reproduction despite perturbations of the internal and external environment.

2. Organic evolution (as opposed to human engineering process or its counterpart) is responsible for extant physiological mechanisms and explains the unity, diversity, and idiosyncrasy evident in these mechanisms. "Nothing in biology makes sense except in the light of evolution," and physiology is no exception. Evolution is "descent with modification."

3. Descent. How and why humans and nonhuman animals work the way they do is largely because these animals have inherited their physiological works from their parents (and in turn from their parents' ancestors).

4. Modification. Natural and sexual selection are potent mechanisms that can modify or maintain physiological mechanisms. These mechanisms result in change (or stasis) that maximizes Darwinian fitness, either in general or in specific environments/contexts, i.e., adaptation.

5. The organism is an essential aspect of physiology.

6. The organism is at the midpoint of a scale of biological organization.

7. Mechanisms for maintenance, growth, and reproduction require matter and energy.

8. Environment.

9. Exchange and equilibration among compartments obey simple rules.

10. Physical mechanisms of exchange through surfaces (e.g. diffusion and like processes) can be manipulated and exploited according to their underlying principles.

11. Exchanges via bulk flow and analogous processes (e.g. circulation, ventilation, axonal and dendritic neurotransmission) can be manipulated and exploited according to their underlying principles.

12. Fluxes of each mass and energy species are as diverse as the physiochemical differences among these species, often compartment specific, must vary dynamically in response to changing supply and demand, and are often coupled with one another. Physiological mechanisms that regulate these fluxes are corresponding solutions to these challenges.

13. The intellectual relationship of physiology to other disciplines is disciplinary coupling (Feder, 2005).

Although the concept taxonomies vary, the mechanisms of a concept-based approach remain the same. Concepts are presented as underlying and guiding principles of physiology, then information about specific systems are presented as examples of where these concepts occur. Overall, the structure of course content in physiology courses for biomedical engineers falls at different points along a system-based – concept-based continuum.

This study experimentally evaluates several questions related to how biomedical engineering students learn physiology and transfer their knowledge and skills to learn subsequent biomedical engineering topics.

1. How does the mathematical approach to teaching physiology, quantitative vs. qualitative, affect how well undergraduate students are prepared to learn subsequent biomedical engineering concepts?

2. How does the structure of course content, concept-based vs. system-based, affect how well undergraduate students are prepared to learn subsequent biomedical engineering concepts?

3. Do undergraduate engineering students demonstrate adaptive expertise as they engage in learning activities in the discipline?

4. Do the components of the adaptive expertise construct that emerge from the literature correlate with high and low scores of adaptive expertise as measured by the Index of Adaptive Expertise?

1.4 Purpose of the Study

The mathematical approach and content structure of the physiology sub-curriculum vary markedly across undergraduate biomedical engineering programs. One of the purposes of this research was to reveal how ABET-accredited programs presented the physiology sub-curriculum. The Whitaker Foundation Curriculum Database provided a valuable starting point (Whitaker Foundation, 2006); however, this database has not been globally updated since before the close of the Whitaker Foundation in 2006.

In addition to physiology topics, the VaNTH Delphi Study looked at important topics for biomedical engineers in biology. They found that academia, but more so industry, has recognized the importance of knowledge to some degree in biochemistry, molecular biology, genetics, cell biology and bioinformatics for biomedical engineers (Linsenmeier & Gatchell, 2008). As these prerequisite topics become more crucial to student learning in new biomedical engineering sub-disciplines, a shared database of biology and physiology sub-curricula could be used in much the same way the Whitaker Foundation Curriculum Database was used by those responsible for the development of BME programs.

With continuing growth in the science and engineering fields, BME students are not only faced with more information, but more opportunity. Physiology is a core component of all biomedical engineering subdisciplines. How students put the initial building blocks of that knowledge together may affect how they learn subsequent topics in the field. The BME undergraduate curriculum does not have space for many additional courses. Whatever approach is used must develop students' self-learning skills or adaptive expertise. Adaptive expertise is exemplified by in-depth factual and conceptual knowledge in a particular domain that can be drawn upon to approach and solve novel problems (Bransford, Brown, & Cocking, 2000). With the sheer quantity of current and potential biomedical engineering topic areas, the development of a core base of knowledge of physiology concepts might better prepare young biomedical engineers for careers in any subdiscipline. Experimental evidence to support best practices for teaching physiology to biomedical engineering undergraduates may provide useful information to BME programs faced with decisions on curriculum and course development.

1.5 Conceptual Framework

The premise of this experimental study was to test the effect of two independent variables, mathematical approach and content structure, on the dependent variable – adaptive expertise. Adaptive expertise is a construct related to transfer of learning that focuses on an individual's ability to use knowledge and experience gained in a particular domain to enhance learning in situations that occur in another domain or in situations that are not anticipated. To test the main and interaction effects, online learning modules incorporating elements of the How People Learn framework and challenge-based instruction have been developed and implemented in a between-subjects research design (Bransford et al., 2000).

1.5.1 Defining mathematical approach

Biomedical engineering programs have long recognized the need for strong overlap between mathematics and life science, particularly physiology concepts. In recent years, the need to integrate more math into physiology, biology and other life science courses has been recommended to help undergraduate life science students better prepare for the interdisciplinary field they will enter (National Research Council, 2002). The Bio2010 report tendered several recommendations for a new curriculum in the life sciences. One of those recommendations specifically addressed adopting a quantitative approach to educating life science undergraduates.

What level of mathematics is required to make a course quantitative in nature? The Bio2010 report used the term "quantitative" to imply that mathematics and computing were essential tools in framing experimental questions, analyzing experimental data, generating models, and making testable predictions. The Bio2010 recommendations (as shown in Table 1-1) included a delineation of important concepts in mathematics and computer science that should be a part of what students learn in biology, physiology and other life science courses (National Research Council, 2002). Additionally, shared resources of quantitative problems in physiology for biomedical engineering curricula typically involve the use of algebra although the infrastructure exists for incorporating more advanced math (Linsenmeier & Gatchell, 2008).

Table 1-1

Quantitative Concepts from Mathematics and Computer Science. **(**Reprinted with permission from the National Academies Press, Copyright [2002], National Academy of Sciences)

Topic Area	**Concept**
Calculus	Complex numbers
	Functions
	Limits
	Continuity
	The integral
	The derivative and linearization
	Elementary functions
	Fourier series
	Multidimensional calculus: linear approximations, integration over multiple variables
Linear Algebra	Scalars, vectors, matrices
	Linear transformations
	Eigenvalues and eigenvectors
	Invariant subspaces
Probability and Statistics	Probability Distributions
	Random numbers and stochastic processes
	Covariation, correlation, independence
	Error likelihood
Dynamic Systems	Equations of motion and trajectories
	Test points, limit cycles
	Phase plane analysis
	Cooperativity and feedback
	Multistability
	Discrete time dynamics
	Sensitivity to initial conditions and chaos
Information and Computation	Algorithms

	Computability
	Optimization
	Bits: information and mutual information
Additional Quantitative Principles	Rate of change
	Modeling
	Equilibria and Stability
	Structure
	Interactions
	Regulation of Potassium in Extracellular Fluid
	Stochasticity
	Visualizing

Conversely, a qualitative physiology course involves very little math. Lecture presentations may include an occasional algebraic expression to help explain a process or concept. However, any summative or formative assessment typically does not require students to use algebra. Only basic arithmetic, including percentages and fractions, is a required prerequisite student skill.

The physiology core requirement for ABET-accredited programs does not specify the mathematical approach for courses. Both quantitative and qualitative courses can be found in ABET- accredited BME programs. To test whether one type of mathematical approach is better than the other at developing students' adaptive expertise, a quantitative test condition and a qualitative test condition were defined for use in the study. There are many mathematical concepts and processes that can be used in quantitative physiology courses. In a quantitative environment, students will need to use these concepts and processes when they are completing summative and formative assessments. On the other hand, in a qualitative course environment, an algebraic expression may only be used in the presentation of concepts and process definitions. The physiology lessons used to test the research questions were developed with these two levels of mathematical approach delineated.

1.5.2 Defining content structure taxonomies

Organizing physiology content for course development and subsequent instruction is a process that requires at least two decisions - what topics to include and in what order to present them. VaNTH presented a set of 19 unifying concepts based on the content and skills that biomedical engineers would likely need to be successful. For the experimental study, these concepts were re-grouped in seven categories (see Table 1-2).

Table 1-2
Conceptual categories for concept-based physiology modules (adapted from Silverthorn, 2002)

Theme	**Concept**
Form	Levels of Organization in the body
	Compartmentation
Function	Structure/Function relationships
	Molecular interactions
	Biological Energy
Physical Properties	Mechanics: movement and associated forces
	Elastic properties
	Bioelectricity
	Emergent properties of complex systems
Variables and Measurement	Biological units of measure
	Scaling in biological systems
	Physiological variables
Information Processing	Biological transduction (molecular/sensory)
	Communication and coordination
Control Systems	Homeostasis/dynamics and control systems
	Mass flow (transport)
	Mass balance
	Heat balance
	Pressure – flow – resistance

The traditional system-based structure focuses on one system at a time, presenting it fully before moving to the next. Many courses are designed to follow the chapters in major textbooks used to supplement physiology instruction (Levy, Koeppen, & Stanton, 2005; Silverthorn, 2006; Widmaier, Raff, & Strang, 2006) or to follow the major interests of the faculty who teach the course. A typical system-based course might follow this progression:

1. Homeostasis: A Framework for Human Physiology

2. Chemical composition of body: atoms, ions, molecules
3. Cells and Tissues
4. Membrane Dynamics
5. Cardiovascular System
6. Blood Components, Flow and Pressure
7. Respiratory System
8. Renal System
9. Nervous System
10. Central Nervous System
11. Sensory Physiology
12. Efferent Peripheral Nervous System
13. Skeletal-Muscular System
14. Control of Body Movement
15. Endocrine System
16. Metabolism and Energy Balance
17. Digestive System
18. Immune System
19. Reproductive System

1.5.3 Adaptive expertise

Adaptive experts are able to use knowledge and experience gained in a particular domain to learn in unanticipated situations. As biomedical engineering continues to evolve and the interdisciplinary nature of the field becomes more intricate, adaptive expertise becomes important for BME graduates as they look to apply their knowledge and skills outside the classroom. The development of adaptive expertise across domains in the biomedical engineering curriculum was one of the goals of the VaNTH ERC (VaNTH, 2007a). In the physiology domain, the ability to break down a complex problem and then to use concepts learned in previous courses (i.e. mass balance, gas laws, work versus heat production) to attack an authentic physiological problem is considered key to developing adaptive expertise (Troy & Linsenmeier, 2003). This premise can be carried forward as students use concepts learned in physiology courses to attack problems and challenges in subsequent BME courses.

Adaptive expertise is closely related to theories of transfer of learning. These theories explore how individuals apply something they have learned to a new problem or situation. One important theory is Preparation for Future Learning (PFL), which is a broader conception of the Direct Application Theory of Transfer which considers an individual's ability to learn in knowledge-rich environments (Bransford & Schwartz, 1999). The PFL paradigm focuses on extended learning by revealing the importance of activities and experiences associated with past learning. The PFL approach provides a framework for assessing particular kinds of learning experiences and the development of adaptive expertise.

Transfer of learning is central to allow students to develop new understandings. Transfer is the ability to extend what has been learned in one context to a novel, unfamiliar context (Byrnes, 1996). There are different theories of transfer each having different implications when assessing learning. The Direct Application Theory of Transfer is the typical approach. In this theory, transfer is characterized by direct application of previous knowledge to a new setting or experience (Bransford & Schwartz, 1999). Usually this knowledge is measured with a methodology that Bransford and Schwartz refer to as "sequestered problem solving." Like members of a sequestered jury, students work to solve the problem at hand without any reference or resource materials. Since the PFL paradigm acknowledges that learning takes place in a knowledge-rich environment, assessments should allow students to interact with that environment as well.

Approaching transfer from the PFL perspective may also require practitioners to move from viewing assessment as static measures to more dynamic measures. Strictly using static assessment methods may fail to show the learning gains of many students. Dynamic assessments allow evaluation of learning when learners have access to scaffolds and resources over a period of time. The environment can be designed with the goal to assess a student's preparation for learning (Campione & Brown, 1987).

1.5.4 Measuring Adaptive Expertise

To quantify levels of adaptive expertise, a metric was originally defined based on research in biomechanics education. Later named the Index of Adaptive Expertise (AdEX Index), this metric includes measures of learning gains in factual knowledge, conceptual knowledge and transfer of learning (Pandy, Petrosino, Austin, & Barr, 2004). Factual knowledge (F) comprises a student's ability to retain key facts and principles. Conceptual knowledge (C) is the ability to understand the underlying principles as well as using quantitative skills to solve a problem. The transfer component (T) measures student ability to extend knowledge to a new situation. The AdEX Index is described by 0.10(F) + 0.40(C) + 0.50(T).

1.5.5 How people learn framework

An important goal in the development of the learning modules for this research project was understanding how to put learners on a path to becoming adaptive experts. The How People Learn (HPL) framework suggests that there are important differences between learning rote facts and developing connections of knowledge and skills that prepare students for ongoing and future learning.

The How People Learn (HPL) framework is based on a review of cognitive science and supports the notions of sense-making, development, insight and meta-cognition (Bransford et al., 2000). The framework provides four overlapping portals from which to view learning environments:

- **Learner-centered** where environments focus on the knowledge, skills, and attitudes that students bring to the learning situation;
- **Knowledge-centered** where environments focus on content that is organized around core concepts;
- **Assessment-centered** where environments help students' thinking to become more visible so that understanding can undergo assessment and revision;
- **Community-centered** where environments capitalize on local expertise to create a sense of collaboration.

Knowledge, skill and understanding are the currency of education (Perkins, 1998). Knowledge and skill are readily assessed when a student is asked to reproduce what he or she knows or to perform a learned task. Understanding is not so easily recognized. Perkins defines it as the ability to think and act flexibly with what one knows. Assessing understanding requires a performance criterion that goes beyond rote and routine.

The performance view of understanding can be contrasted to the representational view of mental models. Mental models are representations of mental objects that people manipulate internally by using meaning and general knowledge already internalized (Johnson-Laird, 1983). The How People Learn Framework emphasizes learning with understanding, yet recognizes that it is difficult to assess. The performance criterion model can lead to a construct of understanding that is more measurable.

1.5.6 Challenge-based instruction and the STAR.Legacy cycle

Challenge-based instruction with its open-ended problems is an effective approach to help students improve their ability to apply learning to both current and novel situations. Challenge-based instruction is a model that incorporates the four learning portals of the HPL framework into an effective learning environment. It is one of several approaches that can be categorized as inquiry-based learning (Prince & Felder, 2006). Inquiry-based learning is a pedagogical approach that sets the stage for students to work independently to acquire the knowledge they need to solve a problem. In this active learning model, the role of the teacher is to facilitate the process of knowledge-discovery.

Challenge-based instruction is characterized by presenting students with a challenge problem that needs to be solved. The challenge problem is typically open-ended and requires students to integrate several concepts in order to find a tenable solution. From this standpoint, challenge-based instruction is an effective tool for engineering instruction as it matches the problem-solving nature of engineering with the open-ended nature of design. The learning facilitator structures the environment to encourage student engagement with the course materials while providing appropriate feedback to move the students toward a solution.

Challenge-based learning models fit well with collaborative knowledge construction. "Collaborative knowledge construction" is a term used to describe the cognitive processes at play in collaborative learning (Dillenbourg, Baker, Blaye, & Malley, 1996). In collaborative challenge-based learning, students are working together to solve a complicated problem. This process has a twofold benefit. First, the cognitive load can be distributed among group members. Additionally, the group benefits from distributed expertise (Pea, 1993). Although, this research focused on the achievements of the individual learners, elements of collaborative knowledge construction played an important role. The socio-cognitive actively fosters the process of collaborative knowledge construction through the use of structuring tools and scaffolding in the online learning environment (Weinberger, Reiserer, Ertl, Fischer, & Mandl, 2003).

The STAR.Legacy (SL) Cycle is a proven model of challenge-based instruction that creates a rich environment for collaborative knowledge construction (Schwartz et al., 1999); Giorgio & Brophy, 2001; Leelawong et al., 2001). The SL cycle is based on three general principles of instruction:

- Knowledge should be presented in context
- Students should be given opportunities to generate ideas and demonstrate what they know
- Multiple contexts should envelop knowledge

The SL Cycle evolved as a way to implement the HPL framework. The model grew out of collaborations with teachers, trainers, students, curriculum designers and researchers working to create a structure for challenge-based learning (Schwartz, Lin, Brophy, & Bransford, 1999). This design has been successfully implemented in undergraduate engineering courses (Cordray, Harris, & Klein, 2007). The phases of the SL Cycle can be implemented in any lesson from any curriculum (see Figure 1-2). Although not explicitly included in the cycle, in association with the presentation of the challenge, an initial activity might be to state the learning objectives.

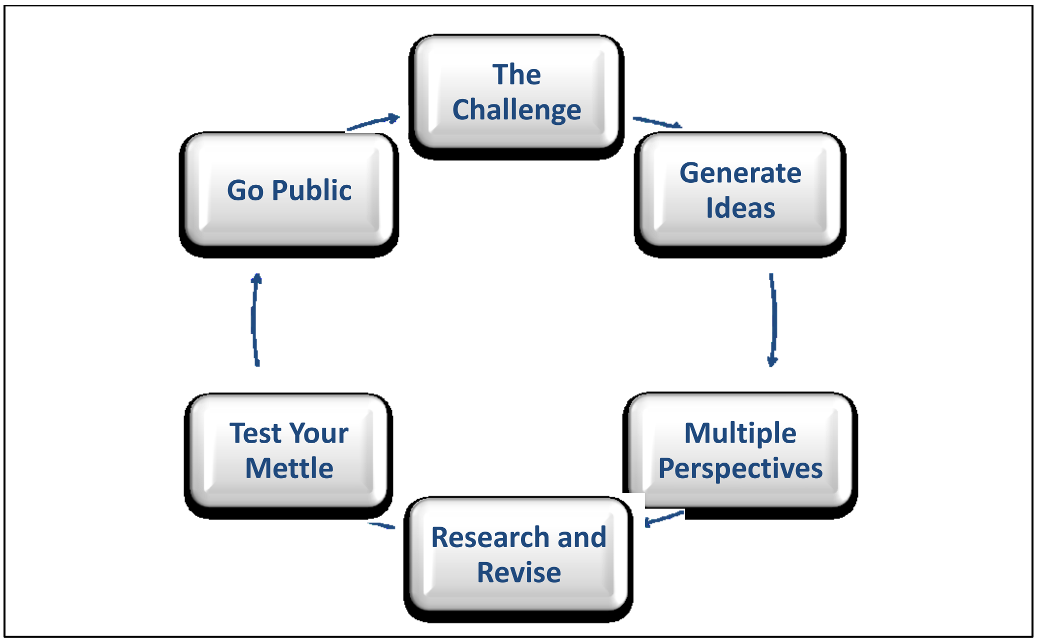

Figure 1-2. Steps of STAR.Legacy Cycle (Schwartz et al., 1999)

The components of the SL Cycle form consistent, but often implicit, steps in learning. Although the phases are presented in an ordered sequence, they do not need to be strictly followed in the order shown. Returning to an earlier phase may be the next rational step for a learner. Several back and forth iterations can occur between two stages. In this way the STAR.Legacy Cycle is considered to be flexibly adaptive (Schwartz et al., 1999).

The six phases of the SL Cycle as described in *A User's Guide to the Legacy Cycle* can be applied to any curriculum. First, a question is presented in the form of a *challenge*. The question should encourage students to want to know more about the topic and become engaged with it. Next, students begin to *generate thoughts and ideas* about the challenge question. The activities associated with this phase involve opportunities for students to compile and share what they may already know about the topic and present their initial ideas and perceptions. Seeking *multiple perspectives* involves accessing outside resources that provide information about the challenge topic. This phase is closely related to *research and revise*, as students seek resources that may include lessons, supplemental text, journal articles or lectures. Based on this new information, students revise their original ideas about the challenge. Formative assessment opportunities are provided in the *test your mettle* phase. These activities allow students to explore what they now know about the challenge and evaluate what they may need to go back and *research and revise*. These two phases are iterative, allowing students to shape their own learning. Finally, the students present a final shared artifact as they *go public* with their results. This final artifact could exist in the form of tests, oral presentations, posters, reports, projects or role-playing (Klein & Harris, 2007)

The learning modules developed for this study incorporated elements of challenge-based online learning. The Vanderbilt AMIGO[3] project has explored ways to use what is known about how people learn to design web-based learning environments (Bransford, Vye, Bateman, Brophy, & Roselli, 2003). The web-based environment makes it easy to adapt learning modules to create new resources and challenges. Challenge-based modules have been developed using a database of generic resources such as audio and video clips, simulations, and texts.

1.5.7 Multi-user virtual environments and role-playing in web-based learning

Engaging and motivating students in web-based instruction is a critical element for learning to occur. The use of role-playing and a multi-user virtual environment (MUVE) are deliberate motivational tools that share many characteristics with popular online games (e.g.

World of Warcraft, Everquest). Online role-playing games typically engage players with specified goals and problems to solve (Salen, 2008). Similarly, challenge-based learning has a problem to solve and learning objectives to scaffold the development of that solution. Elements that engage players in games parallel the elements and learning situations that are designed into challenge-based learning. The game structure itself encourages players to solve a problem. However, that can fall apart if either believability or authenticity is not conveyed. The narrative or back story provides the authenticity of engagement. Just as in the gaming world, problem-based learning must provide authentic content in a believable situation (Royle, 2008).

Like games, challenge-based learning has the power to engage and kindle excitement in learners in a personal way. Success comes from engaging with material at cognitive levels beyond pure recognition and recall. As the student becomes immersed in the challenge, they are able to transfer learning from previous situations to solve new problems. There are several game and simulation features that can be incorporated into learning environments (Rude-Parkins, Miller, Ferguson, & Bauer, 2005):

- Scenario-based challenges
- Scoring based on good decisions
- Learner-controlled timing
- Detailed screen displays, photos and animations
- Lifelike audio and sound effects
- Realistic maps and overlays

Higher education can be served by discovering what game designers do to encourage people to learn complex games. Game designers know how to get participants to enjoy learning. Many of these methods relate to cutting-edge human learning principles that empower learners to solve problems and develop greater levels of understanding (Gee, 2004). Epistemic games, as an example, have been developed around several theories of learning including communities of practice, reflective practice, epistemic frames, and pedagogical praxis. As they play these simulation games, learners enter a world linked to a specific professional practice (i.e. engineering, urban development). Through their interaction with this community, they learn skills and knowledge in a simulated authentic environment (Shaffer, 2004a, 2005).

The modules developed for this study used elements of game-informed learning strategies as study participants engaged in role-playing activities in the MUVE Second Life®. Second Life® is the most used MUVE in higher education. Although virtual environments are not widely used in university settings, their growth has profited from advances in Internet technology and the increasing availability of high broadband wireless networks. Virtual worlds like Second Life® are positioned to play a role in the growing number of university course offerings being taught online.

There are several elements of the Second Life® experience that allow instructors to think outside the box when designing online and hybrid courses. The medium allows for extended and rich interactions. Collaborating in Second Life® is more than exchanged text messages, whether synchronous or asynchronous. Sitting at a conference table in a virtual world and brainstorming with a design team (represented by their avatars in the space) more closely models a real face-to-face interaction (Warburton, 2009) than text-only chat.

1.5.8 Design experiments

It is important to consider the theory and methodology of design experiments within the scope of this research project. Design-based research focuses on the integration of research with the practice of education. This methodology encourages researchers to experiment with intervention designs in a classroom context. More importantly, it frames educational research as a “design science” that requires a methodology to systematically test and revise iterations of a design (Brown, 1992). The design experiment paradigm is most often used to study innovative learning environments that may incorporate technology and complex approaches (Sandoval & Bell, 2004).

Although not carried out in a traditional classroom setting, this research project will involve student participation in online course modules, one example of an educational setting. Examining learning and cognition within the educational setting itself can provide richer findings. Research paradigms that isolate the variables in a contrived laboratory setting will provide incomplete understanding of the interactions that occur in a natural environment (Brown, 1992). Design-based research moves beyond observation as researchers use the data collected in the teaching and learning process to adjust aspects of the context and experimental parameters to further generate theory.

A "design experiment" is an educational research experiment carried out in a complex learning environment usually exploring how some technological innovation affects student learning and educational practice. In a design experiment, the goal is to create a new learning environment through development, testing and revision. In this way, the process has many similarities to the engineering process. Design experiments work well when the learning environment is developed concurrent to the educational process as it was with the learning modules in this study.

The educational design experiment has three stages: preparation, experiment and retrospective analysis (Cobb, Confrey, DiSessa, Lehrer, & Schauble, 2003). The preparation involves clarifying the intent of the study, identifying central organizing themes around a specific domain in order to focus the experiment, and specifying the assumptions that are to be made at the outset of the study. Planning involves determining a starting point, a potential path, and possible endpoints for student learning in order to formulate a design that allows those conjectures to be tested, modified, and tested again. The goal of the design experiment is to improve upon the initial design and gather data that allows for revisions of the initial conjectures to get at the heart of the specific intent of the study. The analysis of a design experiment begins at its onset. This ongoing analysis is aimed at supporting student learning by making revisions in an iterative design process. In addition to the analyses conducted while the experiment is in progress, design methodology includes a retrospective analysis or historical evaluation of the experiment. The retrospective analysis reviews the series of events of the experiment to find emergent and potentially reproducible patterns. The goal of this analysis is to place the design experiment in a context that frames it as a case of the theory, domain and organizing themes that were specified in preparation for the study.

1.6 Research Hypotheses

Undergraduate students take core curriculum courses in advanced biomedical engineering topics for which physiology is a prerequisite. Prerequisite physiology courses for biomedical engineering undergraduates vary in the degree to which math and quantitative concepts are incorporated in instruction. Additionally, the structure of the physiology course can be centered around physiological systems or on key unifying concepts. Both the mathematical approach and the way content is structured in a prerequisite physiology course may affect how students are prepared for future learning. Are students better prepared to learn advanced topics in biomedical engineering if they learned physiology via a quantitative, concept-based approach rather than a qualitative, system-based approach? Three null hypotheses were presented to address this question by testing main and interaction effects.

H_{o1}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a quantitative approach and those who were taught via a qualitative approach.

H_{o2}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a system-based approach and those who were taught via a concept-based approach.

H_{o3}: There is no difference in levels of adaptive expertise based on an interaction between mathematical approach and the way that the course content is structured.

1.7 Importance of the Study

Having a solid quantitative understanding of the unifying concepts of human physiology at an early point in their undergraduate education could allow students to more easily segue into advanced biomedical engineering courses and become better adaptive experts. Biomedical engineers in all subdisciplines are being called upon to have a greater understanding of the interface between engineering and physiology at all levels. Biosystems and biosignal theory now extend to the cellular and subcellular level as genetic networks come into play. BME students may soon need to add courses in biochemistry and cell biology to their schedules. As new findings in engineering and biology merge, drug delivery and pharmacokinetics are becoming key areas in biomedical engineering. Participants of the special sections on drug delivery at the 2005 Whitaker Foundation Biomedical Engineering Education Summit concurred that drug delivery and related areas have become such integral parts of biomedical engineering that all BME undergraduate students should be exposed to these topics (Saltzman & Desai, 2006).

As our technological world advances, so does our need to educate engineers to adapt and flourish in that environment. The National Academy of Engineering cautions against allowing the entire engineering profession and engineering education to fall behind this technology curve. There is a need to anticipate the changes of the next 20 years and prepare future engineers to excel in this new world (National Academy of Engineering, 2004). Now is the time to look at the physiology sub-curriculum of undergraduate biomedical engineering programs and align it with the changes that advances in technology will soon require.

1.8 Scope of the Study

This study focused on the physiology component of the biomedical engineering curriculum in undergraduate engineering programs in the United States. Although the focus is the physiology sub-curriculum in ABET-accredited programs, the results of this investigation apply as well to non-accredited undergraduate programs. The findings of this study may also have import to technically-oriented programs as knowledge of physiology is a requirement in Biomedical Engineering Technology degree programs. Greater understanding of the engineering-life science interface is integral to biomedical engineering education globally.

In evaluating the physiology sub-curriculum, this study was limited to two variables: the mathematical approach of the course (quantitative vs. qualitative) and the way the content is organized (system-based vs. concept-based). In order to create a practical testing environment, the physiology topics addressed have been limited to biofluids; however, findings on how students approach learning these topics should generalize to many advanced BME topics for which physiology is prerequisite.

Following a review of the related literature that provides a conceptual framework for this dissertation, the research contributions are presented. The major research contributions of this work are:

- The development and presentation of a process for converting physiology lessons structured around organ systems to lessons structured around physiology and engineering concepts

- An analysis of collaborative problem-solving spaces in online learning environments and suggestions for instructor facilitation of student collaboration in these spaces
- A comparative case study of undergraduate engineering students with high and low adaptive expertise scores that explores the alignment of the Index of Adaptive Expertise metric with the theoretical underpinnings of the adaptive expertise construct.

Chapter 2 - Background and Literature Review

In this chapter, the background of the development of biomedical engineering undergraduate education is developed. Additionally, several areas of literature that inform biomedical engineering education are reviewed.

The Whitaker Foundation aimed to define research in biomedical engineering as engaged in “a discipline that advances knowledge in engineering, biology and medicine, and improves human health through cross-disciplinary activities that integrate the engineering sciences with the biomedical sciences and clinical practice (Whitaker Foundation, 2006). This includes:

1. The acquisition of new knowledge and understanding of living systems through innovative and substantive application of experimental and analytical techniques based on engineering sciences.

2. The development of new devices, algorithms, processes and systems that advance biology and medicine and improve medical practice and health care delivery.”

Opinions vary on the use of the terms “biomedical engineering” and “bioengineering” (Linsenmeier, 2003; Lithgow, 2003); however, for this discussion the terms will be considered interchangeable. A distinction will be made between biomedical and biological engineering. Where biomedical engineering focuses on medicine and improving human health, biological engineering emphasizes food engineering, agricultural engineering and environmental engineering (Institute of Biological Engineering, 2007).

Many great engineers have contributed to improving human health, although they may not have considered themselves biomedical engineers. In the early 16th century, Leonardo da Vinci (1452-1519) was studying aortic blood flow. Herman Von Helmholtz (1821-1894), a physician, physiologist, physicist and mathematician studied muscle contraction and was the first to measure the speed of nerve impulses. Jean Poiseuille (1799-1869), a physician and physiologist, measured blood pressure with a mercury manometer. Balthasar Van der Pol (1889-1959) built many electronic circuit models of the human heart to study the range of stability of heart dynamics. He then added an external driving signal and was able to simulate a situation in which the heart was driven by a pacemaker. None of these men had a degree in biomedical engineering, but their contributions provided a basis for the field.

2.1 BME as an Academic Discipline

BME emerged as a profession in the mid-20th century and has evolved over the years. Early biomedical engineers were degreed electrical, chemical and mechanical engineers applying classical techniques to problems in medicine and biology. The life science and physiology expertise of these engineers was usually limited to the applications of their specific problems. Programs specifically dedicated to educating biomedical engineers began to appear at universities in the late 1960s. Courses in biomechanics, biomass transport processes, bioelectrical processes, biocontrol systems, biomedical instrumentation and biomedical signal and image processing began to emerge within the traditional disciplines (Ghista, 2000). Typically these programs emphasized key engineering principles and later built bridges to the life sciences (Katona, 2006).

Despite many historical biomedical engineering projects, biomedical engineering is a relatively young discipline in formal education. In 1973, twenty-four universities had undergraduate programs enrolling a total of 852 students. By 1999, the number of programs had swelled to 62 with 5546 undergraduate BME students enrolled (Harris, Bransford, & Brophy, 2002). With tremendous growth in the number of undergraduate programs and students, the percentage of students enrolled in biomedical engineer programs however is less than 4% of the total engineering enrollment (Katona, 2006). That said, biomedical engineering is a popular engineering major at the schools that have undergraduate BME programs (Linsenmeier, 2003).

2.1.1 Undergraduate curriculum development

The National Science Foundation (NSF) has supported many initiatives aimed at curriculum reform and learning technology in undergraduate engineering education. The general goal of these programs is to stimulate bold, innovative and comprehensive models for systemic reform of undergraduate engineering education and to increase the retention of students, especially women and those minorities underrepresented in engineering (National Science Foundation, 2006). In 1999, NSF supported the formation of an Engineering Research Center (ERC) with the vision to transform biomedical engineering education. The goal was to produce adaptive experts by developing, implementing and assessing education processes, materials and technologies that are readily accessible and widely disseminated. The Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center (VaNTH) was to be a working model of how multidisciplinary, multi-institutional groups could define an approach to developing and testing curricula for rapidly evolving knowledge bases (VaNTH, 2007a).

One of the issues regarding biomedical engineering education that VaNTH addressed was to define curricula in biomedical engineering (Linsenmeier, Harris, & Olds, 2002). In evaluating the current state of the biomedical engineering curricula across programs, a common core of coursework was shown to already exist in ABET-accredited programs. Researchers analyzed the frequency with which particular courses were required and found that at least 75% of programs require courses in physiology, biology (other than physiology), mechanics, circuit analysis, computing, materials science, instrumentation and statistics; 71% require a course in transport phenomena. Most of the core content was fulfilled by one course per subject, while design, mechanics, instrumentation and physiology were typically taught in two courses (Linsenmeier & Gatchell, 2006).

Defining the BME curriculum presents a two-fold challenge as the goal is to educate students in fundamental knowledge and provide skill development opportunities in both engineering and biology. Biomedical engineers continue to narrow the focus of their areas of specialization. Linsenmeier (2003) suggests that full consensus on what content knowledge biomedical engineering undergraduates need will never be achieved. The VaNTH Bioengineering Core Curriculum Project was based on the hypothesis that agreement on key elements of the BME curriculum is possible. There should exist a fundamental core to the BME curriculum that all departments offering undergraduate degrees generally agree upon (Linsenmeier et al., 2002).

VaNTH proposed a core curriculum for biomedical engineering programs. The core of this curriculum was comprised of 78 credit hours allowing 18 credits free for specialization areas. The prototype curriculum included topics that should allow BME students to successfully navigate any biomedical engineering sub-field.

Engineering students in typical undergraduate programs in all disciplines find themselves in programs that require around 10% more coursework than other degree programs. The undergraduate programs also take students an average of 4.8 years to attain the degree (National Academy of Engineering, 2004). Adding new required courses to an already full curriculum is not an option many programs consider. Beyond increasing the time spent pursuing the undergraduate degree, alternatives to modifying the core curriculum include eliminating some of the current core requirements and/or streamlining current courses to increase efficiency.

2.1.2 Accreditation and benchmarks

Accreditation is the quality assurance component of curriculum. Standards are in place to assure than an institution and specific program meet the needs of students who want to earn a specific degree. Accredited programs have been recognized as maintaining standards that qualify the graduates for admission to higher, more specialized institutions or for professional practice. In engineering, the Accreditation Board for Engineering and Technology (ABET) is the governing organization. ABET monitors, evaluates and certifies the quality of engineering, engineering technology, and engineering-related education in the United States. Approximately 2700 ABET-accredited programs at over 550 college and universities exist nationwide. There are 73 accredited undergraduate biomedical engineering programs (ABET Engineering Accreditation Commission, 2012).

Not every BME program in the United States is accredited. Accreditation is a voluntary process that is quite extensive. The current ABET criteria have been in place since 1996 when “Engineering Criteria 2000” (EC2000) was approved by the ABET Board of Directors. Mandatory compliance by all accredited engineering programs was required by 2001. EC2000 heralded a change in how programs must meet ABET criteria standards. It is no longer about simply meeting established benchmarks. Programs must focus on continuous improvement, meeting education objectives and program outcomes. More attention is being paid to the accountability of programs by requiring assessment of student learning outcomes (ABET, 2000).

BME programs must create broad goals, called program educational objectives, based on the institution, college and program mission statements. From these objectives, a series of program outcomes are derived. The outcomes are the knowledge, skills, and attitudes expected of graduates of the program. Accredited programs must show where outcomes are addressed within the curriculum and how they will be assessed. Engineering educators must be able to demonstrate student achievement of specific learning outcomes. The learning outcomes have been classified as “soft skills” and “hard skills”. Both types of outcomes need to be integrated into the BME curriculum (Benkeser & Newstetter, 2004). With EC2000, accountability has been put squarely on the shoulders of university programs. The focus on outcomes heralded by EC2000 has required previously accredited programs to re-examine their curricula.

The ABET criteria for accrediting biomedical engineering programs establishes general criteria that must be met for all baccalaureate level engineering programs in the discipline. Any institution that desires accreditation of its undergraduate BME program must show that its program satisfies seven general criteria as well as two criteria for the biomedical engineering program:

1. The structure of the curriculum must provide both breadth and depth across the range of engineering topics implied by the title of the program

2. The program must demonstrate that graduates have: an understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology; the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems (ABET Engineering Accreditation Commission, 2012).

2.2 Learning Sciences and Engineering Education

The ABET accreditation focus on assessing student learning outcomes has generated interest in the learning sciences among the engineering education community. The National Science Foundation has supported several efforts in recent years to improve undergraduate engineering education. The VaNTH ERC was one such effort that was funded specifically to address learning science and learning technology development within the biomedical engineering domain. Research on learning and cognition provided a foundation for improving BME education (Harris et al., 2002).

The ability to define and measure transfer is key to assessing the quality of a learning experience. Transfer involves more than just learning something and then applying it to a novel situation. Past understanding and misunderstanding affect the initial learning of something as well. The ability to directly apply one's previous learning to a new setting or problem has been referred to as the Direct Application Theory of Transfer. An alternate theory considers looking at an individual's ability to learn in knowledge-rich environments emphasizing preparation for future learning (Bransford & Schwartz, 1999).

The difference between how experts and novices attack and solve problems is another area of the learning sciences of particular interest in engineering education. Research has shown that individuals can reach a level of expertise in a discipline without becoming an adaptive expert. Adaptive expertise is characterized by flexible knowledge, skills, self-awareness and attitudes toward new learning that set the stage for lifelong learning (Hatano & Inagaki, 1986; Martin et al., 2006; Martin et al., 2007).

A report from the National Academy of Sciences, "How People Learn: Brain, Mind, Experience, and School" addresses strategies for creating learning environments to encourage transfer for future learning, development of adaptive expertise and active learning (Bransford et al., 2000). The approach in this report has become known as the "How People Learn (HPL) Framework".

2.2.1 Constructivist approach

Constructivism is a theory about knowledge and learning that advances that individuals generate their own understanding and meaning as they learn by reflecting on the experience and generating a set of rules that make sense of the experience (Piaget,1973; Vygotsky, 1978) . Learning is the process of adjusting these rules to accommodate new experiences. Guiding principles of constructivism can be adapted to any environment or discipline including engineering education (Brooks & Brooks, 1993). These principles include:

1. Problems posed to students should be of emerging relevance
2. Learning should be structured around primary concepts
3. The students' points of view should be actively sought and valued
4. Curriculum should be adapted to address students' suppositions
5. Student learning should be assessed in the context of teaching

The constructivist approach rejects the notion that rote learning and behavioral reinforcement drive knowledge acquisition. Instead, the goal is to build or reorder knowledge. Ordering and re-ordering knowledge, testing it out and justifying this interpretation are the underlying principles of constructivist practices (Fosnot, 2005).

2.2.2 How people learn framework

The How People Learn (HPL) Framework is a model based on research in cognitive science in a review biased toward STEM (Science, Technology, Engineering and Mathematics) education (Bransford et al., 2000). The HPL framework suggests that learning environments should be:

- Learner-centered
- Knowledge-centered
- Assessment-centered, and
- Community-centered.

First, in a learner-centered environment, the student's individual abilities are taken into account. These individual abilities, including knowledge, skills, preconceptions, and learning styles, provide a basis for future learning. A knowledge-centered environment creates circumstances that allow students to develop understanding by thinking qualitatively and organizing their knowledge around key concepts. To help facilitate understanding, instructors present rationale and relevant connections to promote transfer of knowledge to new situations. An assessment-centered environment helps students make their thinking transparent so that their understanding can continually be refined. Ample opportunities for formative self-assessment, feedback, and revision should be provided. Finally, the goal of a community-centered environment is to connect a learner's knowledge construction to the contexts in which the knowledge is situated. Additionally, students are encouraged to work with other members of their educational community. Interaction with faculty and peers provides opportunities to receive feedback and to learn.

2.2.3 Transfer and preparation for future learning paradigm

Initial theories regarding transfer of learning emerged from the work of Thorndike and Woodworth early in the 20^{th} century (Thorndike & Woodworth, 1901). Traditionally, transfer has been conceived as the ability to directly apply knowledge or procedures learned in one context to new contexts. That is, the knowledge that students learn in their classes will transfer to novel situations and to problems encountered in subsequent courses or when they enter the workforce. Much of the investment in education is justified in terms of preparing students for future learning so that they may become productive members in a society where workplace needs and demands are in constant flux (Mestre, 2003).

With the Direct Application Theory of Transfer model, assessment of transfer requires an experimental task be used to test whether transfer has occurred or not. The transfer research has typically used sequestered problem-solving tasks. Like a jury is sequestered to prevent them from making decisions based on outside influence, participants in experiments are sequestered from outside resources while completing the experimental task. Assessing transfer in knowledge-rich environments as preparation for how future learning might occur has emerged as an alternative paradigm to the Direct Application Theory of Transfer (Bransford & Schwartz, 1999).

The Preparation for Future Learning (PFL) paradigm emphasizes active learning and metacognitive skills. The active view of transfer requires that learning be viewed as a process rather than a product. Transfer is a dynamic process that requires learners to evaluate strategies, consider resources, and receive feedback. As individuals become more aware of their roles in the learning process and develop metacognitive skills, transfer can be improved (Bransford et al., 2000). Invention activities that require students to evolve early knowledge and intuition have been shown to promote this type of transfer (Belenky & Nokes, 2009; Schwartz & Martin, 2004). Assessment requires a different focus in the PFL model. Static, one-shot measures of "test-taking" do not provide an adequate assessment of learning. Although current knowledge is important, a dynamic assessment of a person's ability to learn over a period of a month might better predict success in a first job after graduation from college (Bransford & Schwartz, 1999). With PFL assessment, students learn while being assessed. Knowledge and skills are evaluated within a situated context and the assessment tool is designed to make student thinking and learning visible (Svihla et al., 2009).

Viewing transfer as preparation for future learning merges with an alternate view that transfer should focus on productive practices of learning and the use of the outcomes of prior learning in a variety of cultural-educational contexts. In presenting this alternative conception, founded in a situative perspective on learning, Hatano and Greeno (1999) criticize the cognitivistic approach to transfer for focusing too exclusively on the initial phase of learning and the resulting acquired knowledge. The old views of transfer fail to recognize that learning and the use of previously acquired knowledge are occurring in knowledge-rich environments with access to external support. From an educational perspective, it is important to capitalize on this new conceptualization of transfer (De Corte, 2003).

2.2.4 Adaptive expertise

Viewing transfer as preparation for future learning leads to viewing learners as adaptive experts. Differentiations have been made between routine and adaptive experts. Routine experts are skilled at applying a learned set of routines to solve a problem. They are technically skilled and very adept working on problems within a familiar domain. Adaptive experts use knowledge and experience flexibly in a new situation to modify existing procedures or invent new ways to approach novel problems (Hatano & Inagaki, 1986). Their approach to problem-solving extends beyond routine competencies as adaptive experts approach challenges to extend their knowledge, not simply apply that knowledge to solve new problems.

Since adaptive expertise is important in fields like biomedical engineering where the knowledge base changes rapidly, helping students to become adaptive experts should be a goal of undergraduate engineering education. The development of adaptive expertise is an active, dynamic process that requires challenging students with opportunities to explore and innovate. Effective teaching and learning strategies that promote adaptive expertise are currently the focus of educational research. Several studies have focused on curricula that promote adaptive expertise specifically in biomedical engineering areas (Fisher & Peterson, 2001; Harris et al., 2002; Martin, Rayne, Kemp, Hart, & Diller, 2005; Pandy, Petrosino, Austin, & Barr, 2004).

Four primary constructs have been identified that together comprise the framework for understanding adaptive expertise in the field of engineering: (1) Multiple perspective, (2) Metacognition, (3) Goals and beliefs, and (4) Epistemology. These constructs describe a mindset that is evident as adaptive experts approach problems within specific domains. Multiple perspective refers to the ability to use a variety of representations and approaches, realizing that there is more than one way to analyze, approach and solve a problem. Metacognition is the individual's use of techniques to self-assess and monitor learning, understanding and performance. When students view challenge as an opportunity for growth, their goals and beliefs are grounded in a level of personal satisfaction for increasing their knowledge or developing new skills. Epistemology refers to how individuals perceive the nature of knowledge. In adaptive expertise, knowledge is viewed as an evolving entity, not a static destination (Fisher & Peterson, 2001).

Adaptive expertise can be characterized as discontinuous or continuous (Martin, Petrosino, Rivale, & Diller, 2006). Under the discontinuous model of adaptive expertise development, routine experts are thought to have a subset of the qualities that define an adaptive expert. As a qualitative shift occurs, a routine expert acquires the habits and attitudes of an adaptive expert. The continuous model suggests that routine experts can become adaptive experts as they gain experiences that lead to innovation, aptitudes and abilities that routine experts lack (i.e. flexibility, metacognition, and pursuit of extended, challenging learning experiences).

Adaptive expertise is not fully acquired in a typical undergraduate education. The experiences that come with work in industry or graduate and postdoctoral research advance one's adaptive expertise. Recognizing this developmental process leads to consideration of how different educational methods can enhance the path to becoming an adaptive expert. One model for the development of adaptive expertise proposes two dimensions of adaptive expertise: knowledge and innovation. Knowledge refers to the taxonomic understanding of the field and innovation involves the ability to perform in novel situations. With learning, both of these dimensions must improve for adaptive expertise to develop (Martin, Rivale, & Diller, 2007).

A metric has been generated that first measured adaptive expertise in the biomechanics domain. It includes measures of learning gains in factual knowledge, conceptual knowledge and transfer of learning (Pandy et al., 2004). In a later study, pre-test and post-test data were compared to the metric as changes in these three elements of adaptive expertise are assessed (Petrosino, Svihla, & Kapur, 2006). The factual knowledge (F) component measured a participant's ability to retain key facts and principles. The conceptual knowledge component (C) measured the ability to understand the underlying principles as well as using quantitative skills to solve a problem. Transfer (T) was a measure of student ability to extend knowledge to a new situation. Applying weights to the results of several studies of expertise led to the construction of the metric which was labeled the Index of Adaptive Expertise (AdEX Index). This linear transformation allows adaptive expertise to be measured and compared (Cordray et al., 2009; Klein & Geist, 2006).

$$\text{AdEX Index} = [(0.10*F) + (0.40*C) + (0.50*T)] \qquad \textbf{Equation 2-1}$$

The AdEX Index was derived from research that focused on development of increased conceptual knowledge and students' ability to transfer that knowledge in a novel environment. A different research focus related to adaptive expertise has considered performance on measures of innovation and efficiency (Martin et al., 2005, 2007). Whether conceptual development and transfer or innovation and efficiency are the keys to adaptive expertise, it is evident that development of expertise is a dynamic process that requires deliberate practice on the part of the learner (Litzinger, Lattuca, Hadgraft, & Newstetter, 2011). Creating learning environments that provide students with opportunities to explore, invent, and construct new knowledge can enhance adaptive expertise development (Martin, Benton, & Ko, 2010).

2.3 Inductive Teaching and Learning

The traditional instructional model in engineering education is deductive teaching and learning. With this approach, a topic is introduced in a lecture by a presentation of general principles, derivations, and perhaps some illustrative examples. Students are assigned similar problems and derivations to practice their ability to apply the principles from the lecture. Learning is assessed by testing a student's ability to apply the general principles to a new problem on an exam.

Inductive teaching and learning is an alternate approach that begins with specifics instead of general principles. The specific information may include a set of observations, experimental data, a case study, or a complex real-world problem. As learners analyze the specific information they have been given, they generate a need for facts, rules, procedures, and guiding principles that they are either given or helped to discover for themselves (Prince & Felder, 2006). There are several types of inductive teaching and learning methods. Inquiry learning, problem-based learning, project-based learning, challenge-based learning, case-based teaching, discovery learning and just-in-time teaching are all inductive methods with common features. They are all learner-centered, involve active learning, occur in a community-centered environment, and can be characterized as constructivist approaches. These inquiry-based approaches are typically focused on authentic problems that increase student motivation and engagement.

2.3.1 Problem-based learning

Problem-based learning (PBL) has been used in medical education for many years. It encourages students to apply their knowledge to problems that have clinical relevance (Barrows & Tamblyn, 1980). In its original form, problem-based learning is a cyclic process consisting of three phases. First, students encounter a problem that challenges their reasoning skills and provides a focus for the learning process. With the problem specified, the learner moves to a phase of individual self-directed study which takes into account individual ability to absorb information and its potential usefulness. In the final phase, the newly-gained knowledge is applied to the problem and learning is summarized. A new cycle begins with a new problem (Barrows, 1984).

As an overall instructional strategy in engineering education, problem-based learning has several limitations. The nature of engineering is to apply knowledge to new problems. This is different than the medical education paradigm where students are faced with problems in learning situations that mirror problems they may see in practice. In engineering, it is not so much the retrieval of knowledge as it is the application of knowledge to novel situations. Another limitation relates to the solution set. In medicine there will only be one diagnosis or solution, whereas in engineering there is often a range of well-defined options. Engineering problems can usually be solved in myriad ways. A problem-based learning approach may be insufficient in addressing the acquisition of professional problem-solving skills necessary in engineering (Perrenet, Bouhuijs, & Smits, 2000).

Assessing PBL as an educational approach in engineering has been difficult because of the large variation in implementation. Studies that compare problem-based approaches to traditional learning models do not always focus on the same approach. There are large variations in both PBL and traditional approaches that make comparison impossible. The only generally accepted finding related to problem-based learning approaches is that the method produces positive student attitudes (Prince, 2004).

2.3.2 Challenge-based learning

Challenge-based instruction (CBL) is an inquiry approach that shares similar theories for learning with problem-based learning. However, CBL is more collaborative, giving instructors and students the opportunity to work together to solve a challenge and propose a solution to an authentic problem. Problems are posed as a series of interesting challenges that require learners to search for and acquire knowledge and expertise, as needed, to solve the challenges (Cruickshank, Olander, & Module, 2002; Hmelo, Holton, & Kolodner, 2000; Smith, 1988). The CBL approach is based on the principles of learning and instruction of the HPL framework and has been adopted by VaNTH as well as used in many biomedical engineering education settings (Giorgio & Brophy, 2001; Martin et al., 2007; McKenna, Walsh, Parsek, & Birol, 2002).

CBL has been structured around attempts to solve authentic problems that occur in BME domains. The method helps students develop conditionalized knowledge and understanding that is useful when faced with novel challenges. Challenge-based learning must include opportunities to work in multiple contexts, identify preconceptions that are relevant to the problem-solving, formatively assess progress throughout the problem-solving and engage in reflection and revision following the assessment in preparation for some type of summative assessment. This method of inquiry may or may not include opportunities for collaboration with peers (Harris et al., 2002).

CBL environments have been shown to teach and encourage development of adaptive learning strategies (Martin et al., 2006). When compared to traditional learning that employed a lecture-exam methodology, the CBL method led to greater student gains in the ability to use subject knowledge appropriately and efficiently and the ability to think innovatively in new contexts (Martin et al., 2007). Two facets associated with the AdEX Index, development of conceptual knowledge and the ability to transfer knowledge to new areas, have been shown to improve when challenge-based methods are employed (Pandy et al., 2004; Roselli & Brophy, 2001).

2.3.3 Learning cycle models

Many instructional models utilize learning cycles which provide a sequence of thinking and problem-solving activities. One example, the Kolb experiential learning model, has four elements: concrete experience, observation and reflection, forming abstract concepts, and testing in new situations (Kolb, 1984). Through the work of the VaNTH ERC, a method of challenge-based learning was developed around a learning cycle as a means of implementing the HPL framework in the classroom (Martin et al., 2010; Schwartz et al., 1999; VaNTH, 2007a). The original version of the STAR.Legacy cycle had six steps (see Figure 1-2):

1. Students are given a *challenge* that presents the targeted content in a realistic context and establishes the learner's need to know the content and master the skills needed to develop the knowledge

2. Students formulate their initial thoughts, reflecting on what they already know and *generate ideas* about how they might address the challenge

3. *Multiple perspectives* and resources are sought that offer insights into various dimensions of the challenge without providing direct solutions

4. *Research and revise* allows students to extend their learning as they build the knowledge they will need to solve the challenge.

5. To *test your mettle*, assessment activities allow students to apply what they know and identify what they still need to learn to address the challenge. Multiple iterations between Steps 4 and 5 are usually required to meet the challenge.

6. In the final stage, wrap up their learning and *Go Public* to present a report, complete an examination, or in some other demonstrable way, show that the challenge has been met and they have mastered the knowledge and skills specified in the learning objectives.

STAR stands for "Software Technology for Action and Reflection" where one of the actions is to leave a legacy to help the next group explore a particular topic allowing STAR.Legacy to evolve over time (Schwartz et al., 1999). *A User's Guide to the Legacy Cycle* details the steps recognizing the iteration process involved with assessment (Klein & Harris, 2007). The STAR.Legacy Cycle has been used in many recent studies exploring challenge-based learning in engineering education (Martin et al., 2007; Roselli & Brophy, 2001; Smith & Greenburg, 2001; Watai, Brodersen, & Brophy, 2007). Evidence suggests that challenge-based learning leads to gains in innovation and efficiency, two dimensions of adaptive expertise (Martin et al., 2007).

2.3.4 Collaborative knowledge construction

Challenge-based learning affords many opportunities for collaborative problem-solving activities. The SL cycle requires a collaborative effort to engage with a challenge and develop viable solutions. In this socio-cognitive process, collaborative knowledge construction takes place. Students draw upon their individual knowledge and as they share ideas with their co-learners in the process of solving a problem, they acquire new knowledge (Hmelo-Silver, 2004). The collaboration has reciprocal benefits. First, the cognitive effort required to solve the problem is distributed among all of the learners. Then, the learners are able to take advantage of the distributed expertise of the group (Pea, 1993).

Fischer et al. (2002) define four process of collaborative knowledge construction: (1) externalization of task-relevant knowledge; (2) elicitation of task-relevant knowledge; (3)

conflict-oriented consensus building; and (4) integration-oriented consensus building. Learners bring a varied array of knowledge to the challenge or problem to be solved. This prior knowledge is fundamental to building shared knowledge. As students become aware of the knowledge areas of their co-learners, these learning partners become resources for each other (Dillenbourg et al., 1996). As knowledge is shared and learners work to find a common solution, facts, concepts and processes are often interpreted differently by individuals. The consensus-building process that follows in the drive for an agreed-upon solution is a key element of collaborative knowledge building. The different ways that knowledge is interpreted and presented stimulates the cognitive processes that lead to unique individual development of knowledge (Fischer, Bruhn, Grasel, & Mandl, 2002). Finally, the activities that lead to the integration of each learner perspective into the common solution impact the individual learning process within the collaboration.

Instructors or learning facilitators play an important role in fostering collaborative knowledge construction. They must create an environment where the opportunities for collaborative discourse exist and also monitor progress and keep the learning directed towards the established goal. The best learning facilitators follow the tenets of constructivist teaching. They assume the role of a consultant whose purpose in the learning environment is strictly to guide and they provide the structure necessary to allow learning to occur (Hmelo-Silver, 2003). Ultimately the interaction among learners leads to successful learning. The performance of the group is related to the type of interaction. In the development of problem solutions, high performing teams engaged all of the individual perspectives to arrive at a solution, whereas low performing teams ignored and rejected proposals (Barron, 2003). In successful collaborative efforts, knowledge moves from the minds of the learners to become a team's constructive knowledge. Information, communication and technology (ICT) tools can be used to facilitate these effective collaborations (Beers, Boshuizen, Kirschner, & Gijselaers, 2005).

2.4 Teaching and Learning within a Web-based Environment

The number of web-based learning environments in higher education is expanding. The degree to which college courses are presented online varies, but as bandwidth becomes more available and accessibility to the Internet increases on university campuses, more courses are presented entirely or partially online. There is a great deal of variability in the quality of online courses when student achievement and attitudes are considered (Bernard et al., 2004). The tools and standards by which online learning can be most effectively assessed are still being developed. The nonlinear, interrelated components and multiple approaches to knowledge construction that the environment invites and values make assessment challenging (Spector & Koszalka, 2004). As these standards are developed, both the course management structure and the individual web-based technologies must be considered.

2.4.1 Online course management

Course management tools are used to create virtual learning environments. These course management systems are typically used in one of three ways: 1) technology-enhanced learning where online activities are complements to regular classroom instruction, 2) mixed-mode learning where occasional face-to-face on-campus learning is complemented by online learning activities, and 3) complete online learning which exclusively uses course management based online learning activities (Papastergiou, 2006). Course management systems provide a framework for creating a learning space where students can interact, collaborate and construct knowledge which fits the socio-constructivist model. Whether online learning represents a small percentage of a course or its entirety, the degree of student involvement is a key factor in student learning (Klobas & McGill, 2010). In this way, online learning does not differ from face-to-face learning.

There are many commercial and open-source course management systems being used in higher education. Moodle™ is a popular open-source platform that is used in many universities. Originally an acronym, Moodle™ is a modular object-oriented dynamic learning environment ("About Moodle," 2011). The open-source nature of Moodle™ keeps it in a state of constant revision as users contribute to its evolution. Moodle™ provides educators with a set of tools to manage the learning environment. These tools allow for both presentation of information and a structure for encouraging collaborative knowledge construction. Static course material (text pages, web pages, web links and labels) can be supported in Moodle™ as easily as interactive material (assignments, choice, journals, lessons, quizzes and surveys) and collaborative instruments (chat, forum and wikis).

2.4.2 Web 2.0 technology

As the technology environment evolves, web-based learning environments become more complex with new possibilities for teaching and learning. Web 2.0 applications are poised to change the virtual learning environment. These applications differ from the information and communication technologies that allowed the web to evolve as a broadcasting medium. Web 2.0 tools focus on user participation, openness and the power of networks (O'Reilly, 2011).

Web 2.0 tools in higher education fall under several categories (Conole & Alevizou, 2010; Crook, Cummings, Fisher, & Graber, 2008):

- Media sharing
- Media manipulation and data/web mash-ups
- Instant messaging, chat and conversation vehicles

- Online games and virtual worlds
- Social networking
- Blogging
- Recommender systems that aggregate and tag user preferences
- Wikis and collaborative editing tools
- Syndication via RSS feeds

These tools allow for online learning to move from a distributive focus to a collaborative learning model. The use of Web 2.0 technologies is not about new tools as much as it is a paradigm shift in how those tools are used in teaching and learning. The social networking and collaborative nature allow users to share information and construct new knowledge in efficient and effective ways (O'Reilly, 2011).

Web 2.0 technologies readily support the socio-constructivist pedagogical ideals popular in higher education; however they have slowly been adopted in practice. A review summarizing the paucity of these tools in online learning indicates that instructors have not yet had time to assess the tools themselves and evaluate how they might improve instruction or even be relevant in the context of their learning goals (Conole & Alevizou, 2010). Web 2.0 has the potential to change the way teaching and learning take place, but implementing these tools will require challenging the traditional instructional model in higher education and blurring the boundary lines of the learning and social environments of the next generation of students (Brown, 2010).

2.5 Games and Simulations in Online Learning

Games are engaging. They motivate players to spend time learning them and continuing to interact with them. In recent years, using games as vehicles for learning within the existing educational system has been investigated (Gee, 2003). In fact, the way that individuals interact with games is similar to the pedagogy of problem-based learning. Players must accumulate the tools and experience in order to solve the problems that promote them to higher levels of the game. The game itself provides the purpose for learning by engaging participants with meaningful problems to solve (Royle, 2008).

2.5.1 Games vs. Simulations

The methods that game designers use to engage people to learn a new game are similar to learning principles in the problem-solving domain. Problems in good games are sequential. The problems faced early in the game are designed to help players learn to make good guesses and decisions as they proceed to the more difficult problems at later levels. Players learn solution strategies that work as the tasks get more difficult. Learning is effective when new challenges are just at the outer edge of an individual's ability. Good games are challenging but users have a sense that they can do the task that has been presented to them. Expertise is developed through many iterations of practice until skills become automatic. Games provide cycles of extended practice and tests of mastery followed by a new challenge that begins the cycle over again. Game designers have learned that individuals typically do not use verbal information well when it is not situated in context. To overcome this shortfall, games give verbal information "just in time" (i.e. when a gamer can put it to use) and "on demand" (i.e. when the gamer wants the information) to support learning (Gee, 2004).

Simulations are often used in problem-based learning to engage students in the inquiry process. There is a difference between games and simulations. Games are competitive and require players to apply knowledge to advance and eventually win. Simulations are open-ended exercises with many interacting variables. In a simulation, the goal is for participants to take on a role and address and solve the problems that arise in a given situation. There are several important characteristics of simulations. Foremost is the validity of the simulation game which is determined by how adequately the simulation represents the real-world model. Additionally, each participant must have a defined role with defined responsibilities and constraints. There must be a rich, authentic environment that allows several strategies to be tested and different directions allowed as decisions are made. Finally, participants must receive feedback as they make choices that effect change on the problem at hand (Gredler, 2004). Effective simulations in education require authentic and relevant scenarios that tap users' emotions and force action. A sense of unrestricted options and replayability are necessary (Aldrich, 2005). Simulations are challenging and require active engagement on the part of the learner.

With epistemic games, experts help novices develop expertise in their shared domain. Within the simulation framework, learners enter a world linked to a specific professional practice (i.e. engineering, urban development) and develop new skills and knowledge in a simulated authentic environment. These games use several theories of learning including communities of practice, reflective practice, epistemic frames, and pedagogical praxis (Shaffer, 2004b, 2005). A community of practice is a group of individuals, real or virtual, with shared knowledge and similar strategies for solving problems. Reflective practice occurs when individuals act in a particular situation and then reflect on the results of those actions with peers and mentors, as often happens in professional communities. How an individual acts and reacts within a professional community is organized by a way of thinking – an epistemic frame. Different professions have different epistemic frames within which novices become acculturated. All of these connections are important in designing educational games immersed in the authentic learning environments of epistemic games. Pedagogical praxis is a theory that helps one to understand the relationship between activity and learning in the context of professional learning practices (Shaffer, 2004a, 2005).

2.5.2 Multi-user virtual environments

Multi-user virtual environments (MUVEs), or virtual worlds, are gaining popularity as teaching and learning spaces. Virtual worlds are computer-generated displays where users have a sense of being present in and interacting with an environment other than their real-world environment (Schroeder, 1996). The sense of being present in a virtual world is very important. Presence is ultimately achieved when the user no longer is aware that they are involved in a mediated experience (Lombard & Ditton, 1997). There are two types of presence: physical (or spatial) and social. Physical presence refers to being physically located somewhere whereas social presence is the sense of being with others in an environment. Strong positive correlations have been reported between engagement in a virtual world and social and spatial presence (Vrellis, Papachristos, Natsis, & Tassos, 2010).

Virtual worlds differ from massively-multiplayer role-playing games like *World of Warcraft* and *Everquest*. These role-playing games typically present the user with a goal to achieve either independently or collaboratively (Salen, 2008). Virtual worlds, in and of themselves, do not have quests; users are free to interact and explore the world on their own accord, with or without specific goals in mind. Any purpose in the MUVE must be created or built. The flexibility afforded by virtual worlds enhances their appeal to educators.

These three-dimensional worlds provide opportunities for synchronous communication and collaboration that have heretofore only existed in real, face-to-face environments. The increase in wireless technology and available bandwidth has piqued interest in online education and the use of virtual worlds. Much of that increased interest has been focused on Second Life®, a 3-D public virtual environment launched by Linden Labs in 2003. In 2008, Linden Lab reported that over 300 universities were using Second Life® for teaching or research activities (Michels, 2008).

The structure and concept of 3D virtual worlds make them effective constructivist learning environments. Learners have many opportunities to interact with and manipulate objects in the environment. These interactions are self-directed and learner-centered. Learners are able to experiment and learn by doing in virtual worlds without the repercussions that may exist in real-world environments (Dede, 1996). The collaborative aspect of a multi-user virtual environment supports teaching and learning based on socio-constructivism. Whether it is the freedom granted by the masked identity of an avatar or the shared experience of the virtual world itself, collaboration and peer mentoring are common among learners within the environment (Dickey, 2003).

The virtual environment supports the fundamental constructivist idea of the instructor as a facilitator. Teaching in the virtual world requires consideration of the roles the environment will play in learning. Facilitating learning involves managing the interplay of five key roles the virtual world plays in active learning: location, context, content, community and material (McKeown, 2009). An instructor must provide a location for the learning to occur. In Second Life®, this can include the virtual location in which the avatars will meet as well as the inventory that each avatar possesses. The instructor can place items in the environment that are available on demand. Location will also include virtual audio visual elements that match the same type of elements found in the physical world (e.g., whiteboards, Web pages, videos). Related to location is the context within which learners are immersed in the environment –locations visited or specific inventory used or worn by the participant or facilitator. Because teaching and learning in Second Life® is an immersive experience, content is experienced as participants engage with different locations and contexts. Community is realized as learners engage with other people they encounter in the virtual world. Finally, the virtual world can serve the role as the object of study itself. All action in the learning environment can be recorded in a process called *machinima* which uses 3D graphics tools to create a cinematic production.

Students find Second Life® enjoyable and self-report that it increased their learning and engagement in courses (Jarmon, Traphagan, & Mayrath, 2008). Learning material has a greater appeal to students when presented in the 3D virtual world than when presented in a two-dimensional web browser (Vrellis, Papachristos, Bellou, Avouris, & Mikropoulos, 2010). The ability to create an authentic environment in which students want to spend time is the great advantage of Second Life® and other multi-user virtual environments.

2.6 Physiology Sub-curriculum

One of the ABET criteria requires that biomedical engineering program graduates have the capability to understand biology and physiology and apply advanced mathematics, engineering and science to solve problems where engineering and biology come together. Meeting this criterion raises the importance of the physiology sub-curriculum in BME programs. In over 75% of all undergraduate BME programs, at least one course in physiology is required (Linsenmeier & Gatchell, 2006). Enhancing the physiology sub-curriculum can benefit students in engineering fields beyond biomedical engineering. The *Engineer of 2020* in any discipline will require a basic knowledge of physiological and biological systems as technology and life sciences converge (National Academy of Engineering, 2004).

2.6.1 Physiology curriculum in the life sciences

There has been a call to integrate more mathematics into physiology, biology and other life science courses to better prepare students for the interdisciplinary field they will enter (National Research Council, 2002). The Bio2010 report tenders several recommendations leading to the creation of a new curriculum in the life sciences. One of those recommendations specifically addresses adopting a quantitative approach to educating life science undergraduates by integrating the teaching of math and life science concepts. The Bio2010 report asserts that mathematics and computing are essential tools in framing experimental questions, analyzing experimental data, generating models, and making testable predictions in life science disciplines. Physiology as a sub-discipline of the life sciences has been at the forefront of integrating quantitative elements into the curriculum. The quantitative nature of physiological processes requires incorporating basic principles of physics and engineering. Physiology is, in fact, the integrative discipline in biology (Silverthorn, 2003).

2.6.2 Physiology in the BME curriculum

Physiology is a core topic for all biomedical engineers whether their intention is to practice medicine, work in industry or do biomedical research. There is wide variability in how physiology is incorporated into the BME curriculum. Two basic patterns have emerged. The first approach is to have BME students take a life sciences physiology course with students in other disciplines at their university (i.e. pre-medical, biology, nursing). These students often receive in-depth exposure to physiology; however the content is not presented using quantitative or mathematical descriptions. The second approach utilizes engineering faculty to teach the physiology course. These courses often emphasize areas related to faculty strengths and interests. Although they tend to be highly quantitative, the course may minimize the importance of, or completely ignore, some physiology systems of the body failing to give students a broad understanding of physiology concepts and processes they may encounter during their career (Silverthorn, 2002; VaNTH, 2007a).

The importance of physiology in the BME curriculum is echoed by the companies that hire biomedical engineers. The BME industry continues to seek engineers who are able to speak the language of engineering and medicine, have a familiarity with human physiology and pathophysiology, and exhibit educational breadth (Linsenmeier & Gatchell, 2008; Linsenmeier, 2003). An ideal physiology sub-curriculum for biomedical engineers is distinct from the medical school model in that physiology courses should involve engineering concepts and be more quantitative in nature. The physiology course should be both a course in engineering and a course in the life sciences (Troy & Linsenmeier, 2003).

This interdisciplinary model has been applied in engineering; however, it most often occurs in later technical electives as opposed to in an introductory physiology course (DiCecco, Wu, Kuwasawa, & Sun, 2007). An obstacle to an interdisciplinary approach for introductory physiology courses is that BME students often have weak biology and chemistry backgrounds compared with students preparing for health-related fields and traditional life science undergraduate students. Countering that, BME students are often quite interested in applications of the physiology content and have strong mathematics and physics backgrounds. Active learning methods have been effectively used to take advantage of these strengths while accommodating gaps in the students' backgrounds (Cudd & Wasser, 1999).

It is important to realize that physiology is an entire discipline and BME students have little space in their curriculum to cover the field in its entirety. Consequently, an important objective of the physiology sub-curriculum is to provide students with sufficient understanding of physiology that they can acquire further knowledge and understanding as the need arises in their future as either graduate students or professional engineers (Troy and Linsenmeier, 2003).

2.6.2.1 Mathematical approach to teaching physiology

A quantitative mathematical approach can help students frame the process of learning physiology. Thinking mathematically involves an appreciation for the abstractions of mathematics and possession of the competence to use the skills. Five elements provide a framework for thinking mathematically: the knowledge base (e.g. calculus), problem-solving strategies, effective use of resources, mathematical beliefs and affects, and engagement in mathematical activities (Schoenfeld, 1992). Engineering students are required to take several mathematics courses and by the midpoint of their undergraduate learning have been exposed to linear algebra, integrals, derivatives and differential equations. In these mathematics courses, students also learn problem-solving strategies and metacognitive processes that help them apply mathematics to engineering problems (Cardella, 2007).

Finding physiology course materials that utilize the quantitative approach is difficult. Existing textbooks do not emphasize quantitative relationships and have few problem sets that require advanced mathematics. The gap is filled in some areas with simulation packages, particularly in neural and cardiovascular physiology. Many BME physiology instructors have adapted qualitative problems to use in their quantitative courses. Using a courseware authoring system developed by VaNTH, a project to create quantitative physiology problems independent of a particular textbook was started (Linsenmeier & Gatchell, 2008).

2.6.2.2 Structuring physiology content in BME courses

Most physiology courses are structured around organ systems. This approach may have evolved because medical students needed to fully understand each physiological system. Learning each system fully and completely may be advantageous to biomedical engineering students who move onto careers in medicine or medical instrumentation. However, in two courses it is not possible to present the extensive content of a systems physiology taxonomy. Curriculum decisions must be made regarding what information to include in the one or two courses BME students will have in physiology. An additional concern is that systems-based physiology courses do not promote an understanding of the broad concepts that govern physiology. To counter this concern, a concepts-based taxonomy that emphasizes unifying principles and concepts which repeat across physiology systems was proposed (Silverthorn, 2002; VaNTH, 2007a). The key concept taxonomy has been revised as a list of physiology concepts that are relevant to biomedical engineering students. Utilizing How People Learn principles, students could begin to develop their adaptive expertise to recognize where these concepts occur in various physiology systems and transfer their knowledge (Silverthorn, 2002; Troy & Linsenmeier, 2003; VaNTH, 2007a).

In the concepts-based approach, physiological systems are used to provide examples of where concepts apply to various systems. The set of key concepts may vary between instructors of courses; however, the key to this approach is that the system examples do not obscure the key concepts which are the focus (Feder, 2005). As few as seven general concepts can provide students with a framework for understanding most physiological systems. These seven concepts include control systems, conservation of mass, mass and heat flow, elastic properties of tissues, transport across membranes, cell-to-cell communication, and molecular interaction (Modell, 2000). Modell also suggests that the concepts-based approach helps students become better physiological problem-solvers with an ability to predict responses of physiology systems with which they are unfamiliar based on what they know about the underlying concepts.

Chapter 3 - Development of concept-based physiology lessons

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3.1 Abstract

Physiology is a core requirement in the undergraduate biomedical engineering curriculum. In one or two introductory physiology courses, engineering students must learn physiology sufficiently to support learning in their subsequent engineering courses and careers. As preparation for future learning, physiology instruction centered on concepts may help engineering students to further develop their physiology and biomedical engineering knowledge. Following the Backward Design instructional model, a series of seven concept-based lessons were developed for undergraduate engineering students. These online lessons were created as prerequisite physiology training to prepare students to engage in a collaborative engineering challenge activity. This work is presented as an example of how to convert standard, organ system-based physiology content into concept-based content lessons.

3.2 Introduction

Nearly all biomedical engineering (BME) undergraduate students are required to learn physiology. The ABET (formerly, Accreditation Board for Engineering and Technology, Inc.) criteria for BME undergraduate programs require that "the program must demonstrate that graduates have: an understanding of biology and physiology, and the capability to apply advanced mathematics (including differential equations and statistics), science, and engineering to solve the problems at the interface of engineering and biology as well as the ability to make measurements on and interpret data from living systems, addressing the problems associated with the interaction between living and non-living materials and systems” (ABET, 2013). A few accredited BME programs do not include a physiology course in their core curriculum; instead, these programs focus on developing understanding of physiology as students engage in courses in their discipline. The remaining programs require one or two physiology courses taught either by core BME or other bioscience faculty members (Figure 3-1).

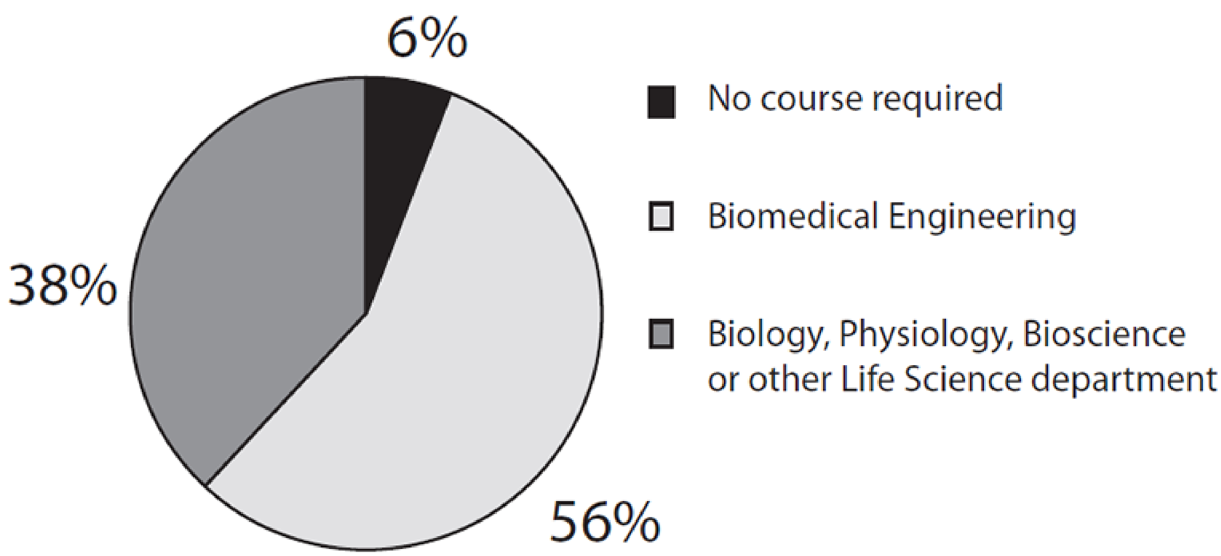


Figure 3-1. University departments teaching physiology courses required for BME students in ABET-accredited programs

These physiology courses are usually prerequisite to discipline-level courses in BME curricula. In the undergraduate curricula of the ABET-accredited BME programs surveyed, there is no standard recommended semester in which these physiology courses are taken. When a course is required, biomedical engineering students in approximately 80% of the ABET programs are directed to take physiology before the end of the first semester of their 3rd year. At this point students have completed most of their general core requirements and are beginning to take their first biomedical engineering courses.

Physiology instruction should help prepare students to solve biomedical engineering problems. Solving engineering problems requires both knowledge and innovation. Preparation for future learning (PFL) is a proposed educational construct related to the ability to innovate. Because every problem cannot be anticipated, the PFL model suggests that instruction should focus on helping students develop their ability to learn as they encounter new situations by making connections to past learning (Bransford & Schwartz, 1999). Physiology instruction, then, should aim to develop a prior knowledge that can support future learning (Schwartz, Sears, & Chang, 2007). What students learn in an introductory physiology course becomes the acquired knowledge from which new connections are made as they continue to learn both new physiology topics and those in biomedical engineering.

For biomedical engineering students, only one or two physiology courses will form the basis of connected learning. In this constrained timeframe, what physiology content should be presented? As ongoing research expands our knowledge of physiology, covering all of the content may become a challenge for physiology in these courses (DiCarlo, 2009). It is important that BME students are prepared to fill gaps in learning as they advance in their subsequent courses and careers. When students have a solid understanding of general physiology concepts, they can continue to add specific content to their knowledge base. Instruction following a conceptual framework offers a potentially better structure upon which BME students can build new knowledge as they advance in the undergraduate curriculum.

Structuring instruction around concepts may influence how students develop knowledge representations. Schema theory focuses on the representations or schemata that a student brings to a learning situation. As students build knowledge, they make connections to prior learning. By making connections between schemata developed with prior learning and new information, students can build a network of structures that represent their knowledge (Hutchinson & Huberman, 1994). Schema theory views learning as making connections to an elaborate network of abstract mental structures that represents an individual's knowledge (Anderson, 1984). This would suggest that the concepts students learn become the schemata to which new information connects.

Focusing instruction on concepts in introductory physiology courses for engineering undergraduate students may better prepare them for future learning of physiology within the BME curriculum than courses which use an organ system presentation scheme. Whereas the system-based taxonomy builds student knowledge around the function of individual organ systems, a concept-based approach builds knowledge around the physiology concepts that occur throughout the various organ systems. Whether a concept-based instructional approach or a particular taxonomy is superior is an unanswered question that will be addressed in future work. As a first step toward evaluating this question, we have created a short series of concept-based physiology lessons specifically targeted to BME undergraduate students. The process used to convert system-based lessons to concept-based lessons is detailed so that instructors and course coordinators can adapt the process to their own curriculum.

Over the years, many physiology concept-based taxonomies have been proposed. Whether emphasizing general models (Modell, 2000), unifying concepts (Silverthorn, 2002), core principles (Michael & McFarland, 2011; Michael, Modell, McFarland, & Cliff, 2009), or core ideas (Feder, 2005), the pedagogical theme has been the same – present the core concepts and exemplify and elucidate with the physiological details. Agreement on a single taxonomy could be important, but an equally fundamental question is “How might a concept-based approach transform course design and classroom instruction?” As consensus develops on the core principles of physiology, and educators begin to define concept-based taxonomies to guide their physiology instruction, the question of how to develop new courses and revise existing courses becomes salient.

A concept-based taxonomy specifically targeting the needs of BME students was developed by physiology and engineering educators working with the VaNTH ERC (Vanderbilt-Northwestern-Texas-Harvard/MIT Engineering Research Center in Bioengineering Educational Technologies) (Figure 3-2). This taxonomy emphasized unifying principles and concepts which repeat across physiology systems. The concepts were eventually categorized into four groups: Introductory Concepts, Anatomical Concepts, Biological Concepts, and Engineering Concepts (Silverthorn, 2002).

There have been recent efforts by physiology educators to establish core principles to be covered in a physiology course, which has led to a proposed list of fifteen core principles (Figure 3-3). Each of these core principles is a top level concept that can be “unpacked” into component ideas that can be developed as learning objectives with measurable outcomes (Michael & McFarland, 2011; Michael et al., 2009). Even though the VaNTH ERC concept-based taxonomy was based particularly on the needs of BME students, there are similarities between the VaNTH taxonomy and these core principles. Several concepts occur in both: *homeostasis*, *communication*, *energy*, *structure/function*, *levels of organization* and *mass balance*.

Introductory

Molecular Interactions
Biological energy
Bioelectricity
Biological transduction
Communication and coordination
Homeostasis, dynamics and control systems

Anatomical

Levels of organization in the body
Compartmentation
Structure/Function relationships

Biological

Biological units of measure
Physiological variables
Scaling biological systems
Emergent properties of complex systems

Engineering

Mechanics (movement and forces)
Elastic properties
Mass flow (transport)
Mass balance
Heat balance
Pressure - flow - resistance

Figure 3-2. Concept categories and concepts of VaNTH physiology taxonomy for BME students (Silverthorn, 2002)

There are differences between the two lists as well. Because the VaNTH concepts taxonomy is engineering-based, all of the concepts, even those not designated as Engineering Concepts, have a quantitative frame of reference. Some of the core principles in the taxonomy developed by Michael et al. do not seem to have a counterpart in the VaNTH taxonomy (e.g., *evolution*, *genes to proteins and physics/chemistry*). Some concepts in the VaNTH taxonomy (e.g., *scaling in biological systems*, *biological units of measure* and *physiological variables*) do not emerge as single concepts among the core principles. Regardless of the specific concepts associated with different taxonomies, the overarching pedagogical goal of concept-based instruction is to provide students with a conceptual framework to support their current and future physiology learning.

Core Principle	Rank
Cell membrane	1
Homeostasis	2
Cell-cell communications	3
Interdependence	4
Flow down gradients	5
Energy	6
Structure/function	7
Scientific reasoning	8
Cell theory	9
Physics/chemistry	10
Genes to proteins	11
Levels of organization	12
Mass balance	13
Causality	14
Evolution	15

Figure 3-3. Core principles in physiology with rankings compiled from responses to a survey of physiology faculty members asked to assess relative importance to the 15 core principles (J.A. Michael & McFarland, 2011)

In the present work, the VaNTH concepts taxonomy for BME students was used as a framework for developing physiology lessons using the Backward Design instructional model

(Wiggins & McTighe, 2005). A single, two-week instructional unit focusing on physiology was created for online instruction of undergraduate BME students. The unit lessons provided prerequisite physiology background the students would need to effectively engage in a collaborative challenge-based learning activity that focused on biofluids engineering topics. All of the lessons and challenge activities were implemented in an online environment that allowed asynchronous and synchronous collaboration.

3.3 Using Backward Instructional Design to Create Concept-based Lessons

Any discussion about developing courses or instructional materials benefits from reflecting upon instructional design principles. Instructional design models are useful for aligning pedagogical goals with instructional materials of any kind. The Backward Design model was used to frame the development of the concept-based lessons we describe in this paper. Backward Design is a course design model that focuses attention first on the specific learning outcomes desired, and then works backward from that point to determine how best to present course content to achieve those learning goals.

The Backward Design process is the same whether instruction is being designed for a series of introductory courses or a single lesson. The first step is to identify the results expected from the instructional unit (i.e., course or lesson). Second, with the expected results articulated, acceptable evidence for achievement is determined: How should students be able to demonstrate their new knowledge? When the learning objectives and assessments are in place, planning the learning experience and developing the course materials are the final steps.

3.3.1 Step 1: Identifying Desired Results of the Concept-based Lessons

Because our goal was to develop concept-based physiology instructional materials to prepare BME students for future learning in biomedical engineering, we first developed BME learning modules that require physiology content knowledge. These modules used challenge-based learning activities that required undergraduate BME students to work in small groups to develop a solution to an engineering challenge question. Challenge-based instruction engages students with open-ended problems to improve their ability to apply learning to both current and novel situations. Each small group of students was presented with one of two challenge questions that focused on a biofluids topic (Figure 3-4). One question required the students to explore giraffe hemodynamics as they addressed the concern of the blood rush to the giraffe's head as it bent down to drink water. The other question required students to consider issues associated with deep diving and the limits of human exposure. Both questions were presented in a scenario that put the students together as a team of interns who were tasked with providing a solution to the problem in the form of a final report. Students were encouraged to generate potential solutions, seek multiple perspectives on the problem, research and revise their original ideas, and collaboratively develop and present their final solution.

The students' first activity in the online instructional unit was to read the introduction to the challenge problem. Then, with the challenge question in mind, they completed the online physiology lessons independently. The giraffe hemodynamics and deep diving challenge problems required understanding of similar physiology subtopics related to blood and oxygen flow, the blood-brain barrier and central nervous system mechanisms. These subtopics were explored in the lessons with targeted content from cell, tissue, cardiovascular system, respiratory system and central nervous system physiology. After the physiology lessons were completed, the students began to work collaboratively on the challenge solution.

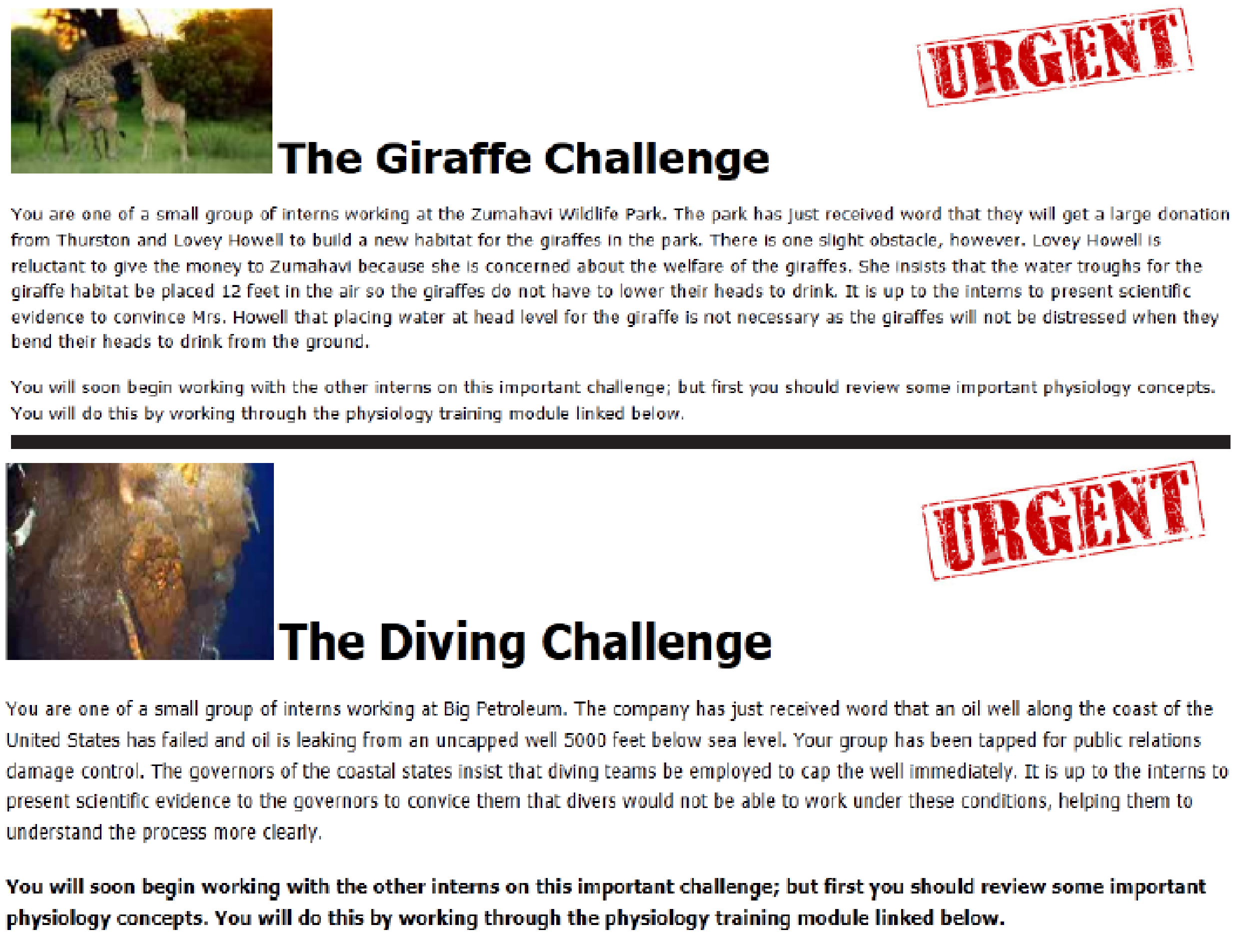


Figure 3-4. Two biofluids questions for undergraduate BME students presented in online challenge learning activity modules

3.3.2 Step 2: Determining Acceptable Evidence for Achievement of Results

To focus the development of the learning materials, ten specific learning objectives were identified (Figure 3-5). To effectively provide the necessary background material from a conceptual perspective, learning objectives related to *pressure*, *flow*, *resistance* and *mass transport* were considered. From a systems perspective, the physiology content that supported these learning objectives related to cells, tissues, the cardiovascular system, the respiratory system and the central nervous system.

The learning objectives were stated in a way that would make achievement easily measurable, which is a best practice (Wiggins & McTighe, 2005). The ten learning objectives were written so that achievement of those learning outcomes was easily evaluated with a pre/post assessment. An instructional activity on a larger scale would have more learning objectives, but the specificity of each objective would be equivalent to those presented here.

Learning Objectives for Physiology Training

After completing the physiology training, the student will be able to:

- Recognize the main points of cell theory
- Identify elements of process of filtration
- Compare and contrast the structure and function of the four major tissue types
- Predict change in blood flow related to heart valve insufficiency
- Analyze a hematocrit value
- Cite examples of the function of blood
- Differentiate blood vessels by function
- Assess effects of capillary filtration given changes in typical pressures
- Summarize function of blood-brain barrier
- Recognize that a pressure gradient is required for respiration

Figure 3-5. Learning objectives for physiology training supporting challenge based learning activity for undergraduate BME students

3.3.3 Step 3: Planning the Concept-based Physiology Instruction

The desired results and specific learning objectives informed the choice of content to include in the physiology lessons. From a review of several introductory physiology texts, specific physiology subtopics were selected for inclusion in the online lessons (see Appendix C for detail). Subtopics were chosen based on two criteria: 1) the topic provided students with necessary background information to solve the engineering challenge and 2) the physiology subtopic itself did not require background information not presented in the lessons. The subtopics chosen were narrowly targeted since the amount of student engagement time was limited. Each lesson targeted one or two learning objectives and was designed to be completed by the student in 30-45 minutes.

Designing instructional material based on a conceptual framework requires a shift in thinking about how physiological details are presented to students. The subtopics as selected from the physiology textbooks were structured according to systems. If this targeted content was placed in a series of seven system-based lessons, the lesson topics would include, in order: cells, tissues, the cardiovascular system, the respiratory system, blood, blood vessels and the central nervous system. Developing the concept-based lessons required a realignment of this system-based presentation of topics. The VaNTH conceptual taxonomy (Silverthorn, 2002) was used to frame the concept-based lessons. The nineteen concepts of the VaNTH taxonomy were aligned into seven lessons. In order to integrate these subtopics in the lesson content, the associated VaNTH concepts were clustered in seven groups of like concepts and given a representative lesson name (Figure 3-6). To achieve the best fit concepts grouping for this learning activity, the amount of content to be included in each category was considered along with trying to maintain lessons that fit the 30-45 minute timeframe.

With the concept grouping established, the physiology content was associated with the predominant concept or concepts and placed in one or more of the seven lesson groups. Some physiology topics were presented to the students as part of multiple concepts. Topic areas were introduced and associated with one concept in an early lesson then further developed with a different concept in a later lesson. The presentation of the *formed elements* subtopic is an example of this strategy. The content related to red blood cells was distributed between two concepts: *molecular interactions* and *physiological variables*, which were found in two different lessons. As another example, information about baroreceptors and chemoreceptors was presented to support the development of both the *biological transduction* and *homeostasis/dynamics and control systems* concepts. In each of these examples, the physiological details of the subtopic that supported or provided evidence of one particular concept were the only aspects presented in the lesson.

Lesson 1: Form	Levels of organization in the body Compartmentation
Lesson 2: Function	Structure/function relationships Molecular interactions Biological energy
Lesson 3: Physical Properties	Mechanics: movement and forces Elastic properties Bioelectricity Emergent properties of complex systems
Lesson 4: Variables & Measurement	Biological units of measure Physiological varaiables Scaling
Lesson 5: Information Processing	Biological transduction Communication and coordination
Lesson 6: Control Systems	Homeostasis/Dynamics & Control systems Mass flow (transport) Mass balance Heat balance
Lesson 7: Pressure/Flow /Resistance	Pressure - Flow - Resistance

Figure 3-6. Realigned concept-based taxonomy lessons for the physiology learning module for undergraduate biomedical engineering students

In the lessons, each concept was first presented and defined (see Figure 3-7 for an example). After the concept was defined, the related subtopic information was developed in a lesson format. Unlike a system-based presentation that builds from cells to tissues to organ systems to organs, the concept-based presentation did not have an established order. However, it was important for introductory topics to be covered in early lessons so that knowledge could build. In the *Form* and *Function* lessons, concepts often considered fundamental were introduced. In the *Form* lesson, these included cell theory, the structures of the cell membrane, tissue types and plasma elements. The *Function* lesson took a second look at some of these subtopics as students then considered the function of the cell membrane and tissues and identified blood components and functions. Additionally, within each of the seven lessons, the order in which the concepts were presented was flexible. This allowed for the complexity of the individual lessons to build. For example, the concept *homeostasis, dynamics and control systems* was presented before *mass transport* in the *Control Systems* lesson, with content related to homeostasis supporting the advanced topic of *mass transport*. Figure 3-8 provides a process diagram of the conversion of the instructional unit from a system-based structure to a concept-based structure.

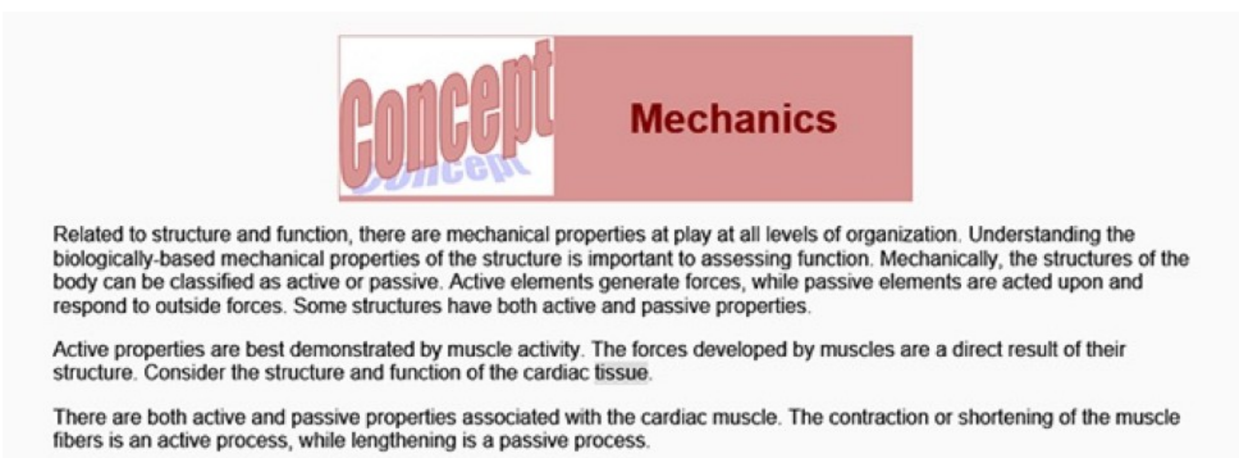


Figure 3-7. Introductory presentation of a concept in an online physiology lesson

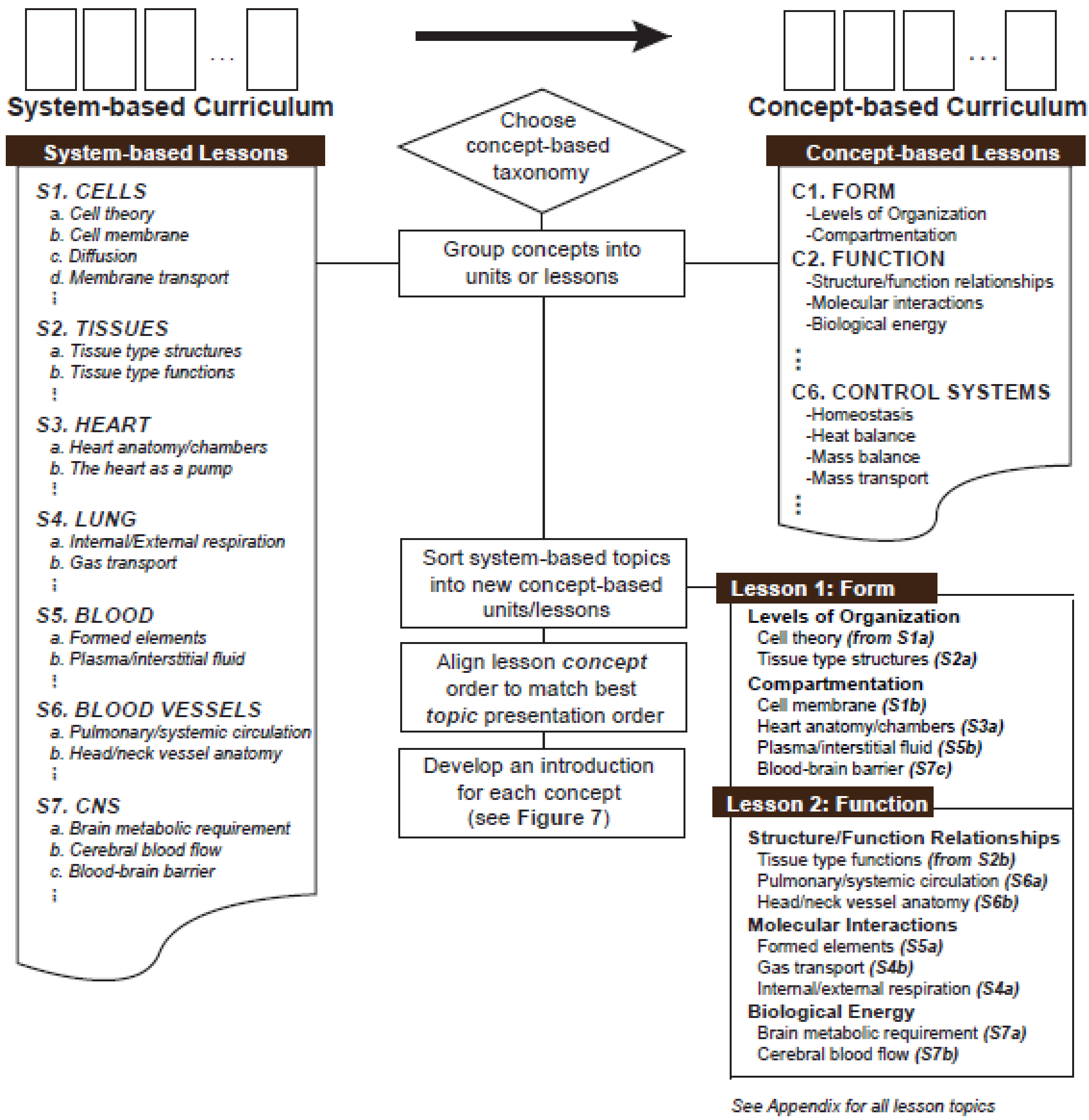


Figure 3-8. Process diagram showing strategy to convert seven system-based physiology lessons to seven concept-based physiology lessons

3.3.4 Step 4: Developing the Course Materials

The multimedia lessons were created using the Moodle™ lesson activity tool. The online materials on the Moodle™ course site included the physiology lessons, a series of four biofluids lessons that provided specific information related to each challenge question, a discussion forum for group collaboration, and a wiki for the collaborative development of the solution. Although not required viewing, the learning objectives for each lesson were presented as a text file that the students could view. Before moving to the next lesson, students were required to complete a set of review questions that assessed their understanding of the lesson content. Using the quiz tool in Moodle™, formative feedback was automatically provided to the respondent at the end of the quiz. This gave students an additional opportunity to review the material. Wiki technology was incorporated to allow students to construct their final reports. The students could write on the wiki either individually or collaboratively and each revision was documented. Additionally, the groups met in the multi-user virtual environment Second Life® for a brainstorming meeting and a final wrap-up meeting as they developed their final solution and wrote their report in the Moodle™ wiki (“Moodle,” 2013; Second Life®, 2008). The concept-based physiology lessons developed for this learning activity can be viewed online (https://courses.moodle.wisc.edu/prod/course/view.php?id=66).

3.4 Discussion

In this work, concept-based physiology lessons were developed to prepare BME undergraduates to use physiology knowledge in future BME courses. We used the VaNTH taxonomy, which was designed for biomedical engineering curricula, to define the concepts, but it is not so different from other taxonomies that the process herein described for creating concept-based lessons is exclusive to this engineering taxonomy. Each taxonomy parses physiology content into a list of concepts that guide understanding of physiology. The concepts associated with each taxonomy are found throughout the physiological content students learn in introductory or survey courses.

By anchoring the physiology lesson development around the specific learning goals for BME students, concept-based lessons were created to prepare students to engage with one of two engineering challenge activities: giraffe hemodynamics or deep diving. The Backward Design process was used because it focused the development of the lessons specifically on learning outcomes. In this example the learning objectives included physiology knowledge that supported the students' exploration of new engineering topics related to biofluids. That particular learning goal focused the choice of subtopics to include in the lessons.

The flexibility to realign the nineteen concepts of the VaNTH taxonomy into seven lessons was essential. When developing instructional materials on a small scale like this physiology training for engineering challenge modules, it was important that each element served a pedagogical purpose. Grouping the concepts around the targeted physiology subtopics allowed the lessons to be focused. Nineteen concepts, seven lessons, and the list of necessary subtopics were the three design factors that influenced how the concepts were aligned. An optimal combination of concepts for each lesson eventually surfaced for this specific learning situation. If a different concept taxonomy had been chosen, the lesson grouping that best fit the course objectives would likely have been different.

From a student perspective, many obvious differences can be found when comparing the end-product of seven concept-based lessons to seven system-based lessons. First, the lesson names will completely differ. Second, the topics will ultimately be presented in a different order. Third, within the lessons, the headings used to highlight the subtopics will not be the same. A comparable set of system-based lessons might build on C*ellular physiology, Cardiovascular physiology, Respiratory physiology,* and *Neural physiology*. Contrast this to the concept-based lessons built around *Form*, *Function*, *Physical properties*, *Variables and measurement*, *Information processing*, *Control systems*, and *Pressure-Flow-Resistance*. The building blocks of the concept-based lessons are an array of concepts that make learning physiology in this manner distinctive.

From the instructor perspective, we found that creating concept-based lessons does not involve extensive rewriting of system-based content. Although new material may need to be created to provide instructional descriptions of the concepts, content describing the subtopics from a system-based lesson can simply be presented in a different order and elaborated upon as an example of how the concept manifests in particular organ systems. Introduction of a concept prior to providing the detail of the physiology examples from different systems may allow students to learn more holistically as they form connections to gain an understanding and an appreciation of the new physiology knowledge.

3.5 Summary

A concept-based introductory physiology course may be particularly effective for BME students. Biomedical engineering undergraduate students will likely take one or two physiology courses in their academic career. With exposure to all concepts of a taxonomy, engineering students could gain an appreciation of the complete conceptual framework of physiology. Additionally, within this framework, students could connect new physiology information encountered over a lifetime allowing future physiology learning to develop. By learning the concepts that describe all physiology processes, students may more easily create mental models or schemas that serve as connections for learning transfer.

Biomedical engineers will be required to continually fill in the gaps in their physiology knowledge as they acquire new biomedical engineering knowledge. The ability to fill those gaps may not rely as much on what a student learned in an introductory physiology course as what they were able to continue to learn about physiology after taking an introductory course. We hope to explore in future work whether the concept-based approach effectively prepares engineering students for future learning, placing them in a position to become lifelong learners of physiology. In addition, in future work the design model used for this learning activity for undergraduate engineering students could be applied with different concept taxonomies again on a small scale with a specific learning focus or within a larger course where more content is presented.

Chapter 4 – Instrumentation and Pilot Tests of Study Protocol

This chapter describes the development of the learning environments that were the instrumentation for the study. The results of three pilot tests are reported to describe how the instrumentation and protocol were developed.

The hypotheses were tested using a randomized 2 x 2 factorial design with independent groups (Figure 4-1). Testing the hypotheses in this manner allowed some economy of design as well as examination of an interaction effect.

<table>
<tr><td></td><td colspan="2">Content Structure
(Content-based, System-based)</td></tr>
<tr><td rowspan="2">Mathematical Approach
(Quantitative, Qualitative)</td><td>Quantitative,
Concept-based</td><td>Quantitative,
System-based</td></tr>
<tr><td>Qualitative,
Concept-based</td><td>Qualitative,
System-based</td></tr>
</table>

Figure 4-1. Randomized 2 x 2 Factorial Design with Independent Groups used to create physiology learning modules to represent experimental conditions

The two independent variables of interest were mathematical approach (MA) and content structure (CS). Mathematical approach had two levels: quantitative and qualitative. Content structure had two levels: concept-based and system-based. The dependent variable Adaptive Expertise in Physiology (AEP) was assessed as a linear combination of factual physiology knowledge, conceptual knowledge and transfer of physiology knowledge to a biomedical engineering context.

4.1 Instructional Goals

To assess the research question, the same physiology content was developed into four learning modules. Seven general learning objectives informed the content decisions. Since the amount of time each participant would review the physiology training modules was limited to 8-10 hours, it was important that the physiology content be targeted to the objectives. Because the learning modules served as an introduction to physiology, the inclusion of some supporting background content was also required.

The learning objectives were an important design factor in the development of the four different learning modules: qualitative, system-based (QLSB); qualitative, concept-based (QLCB); quantitative, system-based (QTSB); and quantitative, concept-based (QTCB). Although, the seven general learning objectives that the pre/post assessment was based upon were the same, there were slight variations in the learning objectives for each of the modules. The differences between the system-based objectives and concept-based objectives were more pronounced than the differences between the quantitative and qualitative forms of the learning objectives. The seven general learning objectives that were specifically assessed with the pre/post assessment are highlighted (see Table 4-1 and Table 4-2).

Table 4-1 Physiology learning objectives used to structure the learning modules representing the qualitative mathematical approach experimental condition.

System-based Modules	Concept-based Modules
Recognize the main points of cell theory	**Recognize homeostasis as a main point of cell theory (Pre/Post 1)**
Compare and contrast the structure and function of the four major tissue types	**Illustrate how structure and function of body tissues are related (Pre/Post 2)**
Identify a normal hematocrit value for a healthy adult male (Pre/Post 3)	**Identify a normal hematocrit value for a healthy adult male (Pre/Post 3)**
Cite examples of the function of blood (Pre/Post 4)	Identify the gases that interact with the hemoglobin molecule in the process of respiration
Differentiate blood vessels by function	**Differentiate blood vessels based on their elasticity (Pre/Post 5)**
Assess effects of capillary filtration given changes in typical pressures (Pre/Post 6)	**Assess effects of capillary filtration given changes in typical pressures (Pre/Post 6)**
Summarize function of blood-brain barrier (Pre/Post 7)	**Summarize function of blood-brain barrier (Pre/Post 7)**

Table 4-2 Physiology learning objectives used to structure the learning modules representing the quantitative mathematical approach experimental condition.

System-based Modules	**Concept-based Modules**
Recognize the main points of cell theory	**Recognize homeostasis as a main point of cell theory (Pre/Post 1)**
Compare and contrast the structure and function of the four major tissue types	**Illustrate how structure and function of body tissues are related (Pre/Post 2)**
Analyze a hematocrit value for an adult male	Analyze a hematocrit value for an adult male
Cite examples of the function of blood (Pre/Post 4)	Identify the gases that interact with the hemoglobin molecule in the process of respiration
Differentiate blood vessels by function	**Differentiate blood vessels based on their elasticity (Pre/Post 5)**
Assess effects of capillary filtration given changes in typical pressures (Pre/Post 6)	**Assess effects of capillary filtration given changes in typical pressures (Pre/Post 6)**
Summarize function of blood-brain barrier (Pre/Post 7)	**Summarize function of blood-brain barrier (Pre/Post 7)**

The learning objectives were written for various levels of Bloom's Taxonomy. Bloom's Taxonomy is a model that classifies the way a student thinks into hierarchical levels: Knowledge, Comprehension, Application, Analysis, Synthesis, and Evaluation. Most of the learning objectives were at the lower levels of the hierarchy in part because the learning modules were written at the level of a first course in physiology. For each general learning objective, a pre-test question was developed. An isomorphic post-test question was also created. The Bloom taxonomy level for each general learning objective and the associated pre/post assessment questions can be found in Appendix D**.** The grading rubrics for questions with open-ended responses can be found in Appendix E**.**

To test the research questions, a learning environment was needed where students would have the opportunity to use their new physiology knowledge as they explored an engineering topic. To meet that need, two biofluid engineering modules were developed as collaborative challenge-based learning environments where study participants would be able to work together to solve a challenge question. The modules also provided lessons that students completed independently. As with the physiology modules, several biofluids learning objectives informed the development of the learning material. Eight engineering learning objectives provided the framework for four lessons in the biofluids challenge modules (see Table 4-3). The biofluids learning objectives were assessed with a pre/post assessment (see Appendix F). The grading rubrics can be found in Appendix G.

Table 4-3 Biofluids learning objectives and lesson topics for the challenge-based engineering modules

Learning Objective	Lesson Topic
• Define hydrostatic pressure • Apply hydrostatic pressure equation to make predictions	**Cardiovascular System Basics/ Introduction to Deep Diving**
• Define allometric scaling • Explain how dimensional analysis could be used to solve a problem	**Scaling and Cardiovascular Anatomy**
• Describe transmural pressure and its relationship to absolute pressure • Apply LaPlace's Law to interpret physiological changes	**Capillary and Cerebral Perfusion**
• Recognize equations that model biofluid flow • Differentiate between Newtonian and non-Newtonian biofluid flow	**Cerebral Blood Flow**

A third level of assessment was required to evaluate the independent variable, Adaptive Expertise in Physiology. The AdEX Index (see Equation 3-1) was used to collectively assess learning gains in physiology factual knowledge, physiology conceptual knowledge and the transfer of physiology knowledge in the engineering context (Cordray et al., 2009; Harris & Brophy, 2005). The physiology learning objectives were divided into two categories: factual and conceptual knowledge. Factual knowledge (F) refers to the participant's ability to retain key facts and principles. Conceptual knowledge (C) is the ability to understand the underlying principles as well as use quantitative skills to solve a problem. Transfer (T) is a measure of student ability to extend knowledge to a new situation (i.e., extend physiology knowledge to the biofluid engineering challenge activity). To arrive at a transfer score, each of the seven physiology learning objectives were assessed as the participants engaged with the biofluids challenge module.

$$\textbf{AdEX Index} = [(0.10^*F) + (0.40^*C) + (0.50^*T)] \qquad \text{Equation 4-1}$$

4.2 Instrumentation Development

To create the experimental learning environment for the study, four physiology modules and two biofluids challenge modules were needed. The manner in which the physiology content was presented in the physiology modules had to be representative of the four experimental conditions. The biofluids challenge modules were designed in a way that the study participants could be "observed" using their new physiology knowledge as they explored the engineering topics. In an online learning environment this required tracking each participant's interactions with the material. The learning modules had to be self-contained and completely accessible to study participants via the Internet. Additionally, a virtual conference space was needed where participants could "meet" and collaborate synchronously in small groups.

Creating learning materials as instrumentation required some additional design considerations. Beyond having instrumentation (an online learning environment) that was usable, it was important to consider how the students would use the learning environment. For instance, since the study participants were not part of a class completing the study for a grade, it was determined the amount of time participants could be expected to engage in the entire study was ten to twelve hours over a 2-3 week period. Additionally, the learning activities had to be motivating enough for students to actively participate. While the physiology modules were to be completed independently, the biofluids challenge modules required small groups to collaborate. The learning environment was built to allow participants to communicate and work together.

4.2.1 Physiology training modules – experimental conditions

The first physiology module created was qualitative and system-based. To create the system-based modules, a cell to organ systems approach was used. Details about cells and tissues were first introduced, followed by information about the cardiovascular system, respiratory system and central nervous system. Subtopics were chosen that aligned with the learning objectives. Several physiology text books and Internet resources were evaluated to determine what content would give students the information they would need to complete the biofluids challenge.

To guide the development of the lessons, a list of acceptable evidence of understanding was developed for each topic area (Table 4-4). This list of student evidence of understanding informed the selection of subtopics for each lesson. Lesson content was developed from facts, concepts, principles and generalizations that students would need to know to solve the challenge question, as well as skills, processes and strategies necessary for them to demonstrate understanding. With the learning objectives, evidence list, and subtopics determined, the physiology lesson content was developed for the seven lessons of the qualitative, systems-based physiology learning module.

Table 4-4 System-based physiology lesson names, subtopics and objectives representative of acceptable evidence of student understanding of physiology content

Lesson	System Subtopic	Acceptable level of understanding
1: Cells	Cell theory Cell membrane Membrane transport	▪ Recognize the main points of cell theory ▪ List the structures of the cell membrane ▪ Describe the functions of the cell membrane ▪ Describe membrane transport processes
2: Tissues	Tissue types	▪ List the four major tissue types and the major

	Muscle tissue Neural tissue	role of each ▪ Name the three types of muscle tissue and describe their role in the body ▪ Name the cell types of neural tissue and describe the structure of a nerve cell ▪ Describe the location and role of nerve tissue
3: The Heart	Location and general factors Heart vessels and blood flow Cardiac cycle of heart Stroke volume and cardiac output	▪ Describe location of heart in human body and its size relative to other body structures ▪ Summarize the heart's functions as part of the CV system ▪ Label the two circuits of the heart/CV system ▪ Describe the cell and tissue types that make up the heart ▪ Trace the flow of blood through the heart ▪ Recognize the arteries/veins that supply blood to the heart ▪ Define cardiac cycle ▪ Order the events of the cardiac cycle ▪ Define cardiac output ▪ Define stroke volume ▪ Cite factors that influence cardiac output
4: The Lungs	Respiration Gas Transport	▪ Describe the processes of external respiration ▪ Identify structures of the respiratory system ▪ Trace flow of air through the pulmonary circuit ▪ Explain how pressure gradients affect the flow of air in the respiratory system ▪ Describe the process of diffusion of gases at the alveoli ▪ Compare and contrast gas exchange at the lungs and gas exchange at the tissues ▪ Explain how oxygen and carbon dioxide are transported in the blood
5: Blood	Components of blood Describe major functions of blood Describe compositions and functions of plasma	▪ Describe structure of blood including its elements ▪ Recognize the physical characteristics of whole blood ▪ Recognize average adult hematocrit values ▪ List major functions of blood ▪ Describe the composition of plasma ▪ Compare plasma composition to interstitial fluid ▪ List functions of plasma
6: Blood vessels	Distinguish blood vessel types based on their structure and	▪ Describe the five major blood vessel types ▪ Describe and define the function of Metarterioles

	function	▪ Describe and define the function of anastomoses ▪ Describe the exchange process at the capillaries
	Identify major arteries and veins and the areas they serve	▪ Label major vessels of the circulatory system on a diagram of the heart ▪ Label vessels of the circulatory system on a diagram of the head
7: CNS	Meninges	▪ Describe the location of the 3 meningeal layers ▪ Summarize the function of each layer in protecting the neural tissue
	Brain regions	▪ Label the 6 major regions of the brain ▪ Name one major function of each region of the brain ▪ State the cardiovascular regulatory functions of the medulla oblongata
	Cerebrospinal fluid	▪ State where and how cerebrospinal fluid is produced ▪ Explain how cerebrospinal fluid protects the brain
	Blood-brain barrier	▪ Summarize the energy needs of the brain ▪ Describe the function of the blood-brain barrier

After the system-based modules were developed, the content was reorganized around a concept-based taxonomy. To match the system-based module, seven concept-based lessons were developed to introduce the concepts suggested for physiology in the BME curriculum (Silverthorn, 2002). This concept taxonomy included nineteen concepts in four categories. To create the seven lessons, the concepts were grouped into seven groups of similar or associated concepts.

Before the new concept grouping was finalized, the system-based lessons were reviewed for content that was considered introductory. This was material that provided a framework for understanding physiology content that would be developed in later lessons. The system-based approach for teaching physiology has natural learning building blocks. First lessons teach information about cells, then tissues, then the organs that are created from those cells and tissues.

When these key components have been presented, the lessons in a system-based curriculum focus on each organ and its associated physiology system.

In creating a curriculum without those natural building blocks, it was important to identify critical introductory material to include in the first lessons in the concept-based learning modules. With the key introductory content identified from the system-based lessons, the concepts from the VaNTH taxonomy that were associated with the introductory material were placed in the first concept-based lessons. Using the same idea of presenting key foundational information first, the concept order presentation for each of the seven concept-based lessons was established (Table 4-5).

Table 4-5 Concept-based physiology lesson names, concepts and objectives representative of acceptable evidence of student understanding of physiology content

Lesson	Concept	Acceptable level of understanding
1: Form	Levels of Organization Compartmentation	▪ Recognize the main points of cell theory ▪ Describe the structures of the cell membrane ▪ Identify the four major tissue types ▪ Differentiate between elements of plasma ▪ Describe the structure of the blood-brain barrier
2: Function	Structure/Function Relationships Molecular Interactions Biological Energy	▪ Describe the function of the cell membrane ▪ Compare the structures of the four major tissue types ▪ Summarize major functions of four major tissue types ▪ Identify individual components of blood and their functions ▪ Identify major functions of blood ▪ Distinguish between blood vessel types based on their structure ▪ Identify major blood vessels when shown a diagram ▪ Recognize that cerebral blood flow must remain constant to meet the energy demands of the brain
3: Physical Properties	Mechanics Elastic Properties Bioelectricity	▪ Identify blood vessels, chambers and valves of heart ▪ Trace flow of blood through the heart

	Emergent Properties of Complex Systems	▪ Identify blood vessel types by their function
4: Variables and Measurement	Biological Units of Measure Physiological Variables Scaling in Biological Systems	▪ Explain changes in hematocrit levels ▪ Explain the events of the cardiac cycle ▪ Define and describe factors that influence cardiac output and stroke volume
5: Information Processing	Biological Transduction Communication and Coordination	▪ Describe the role of mechanoreceptors in biological transduction ▪ Describe how cerebrospinal fluid protects the brain ▪ Distinguish metarterioles from anastomoses based on function
6: Control systems	Homeostasis, Dynamics and Control Systems Mass Transport Mass Balance Heat Balance	▪ Describe the various mechanisms that cells use to transport substances across the cell membrane ▪ Describe the process of diffusion of gases at the alveoli ▪ Compare and contrast gas exchange at the lungs and gas exchange at the tissues ▪ Explain how oxygen and carbon dioxide are transported in the blood ▪ Distinguish between capillary exchange processes that occur in the brain and those that occur in other tissues in the body ▪ Describe the role of chemoreceptors and baroreceptors as sensors that maintain homeostasis
7: Pressure/Flow/ Resistance	Pressure/Flow/ Resistance	▪ Describe the processes of external respiration ▪ Identify structures of the respiratory system ▪ Trace flow of air through the pulmonary circuit ▪ Explain how pressure gradients affect the flow of air in the respiratory system ▪ Describe the process of diffusion of gases at the alveoli ▪ Compare and contrast gas exchange at the lungs and gas exchange at the tissues ▪ Explain how oxygen and carbon dioxide are transported in the blood

After the lesson information was determined for the system-based curriculum and concept-based curriculum, two series of web-based lessons were created using the Moodle™

course management system at the University of Wisconsin-Madison College of Engineering. The flexibility of the lesson activity in Moodle™ allowed short content pages to be linked together for ease of navigation. Several user interface principles were considered in the development of the lessons. From a formatting perspective, page length was limited to require no more than one scroll down to see all of the content. Images and short paragraphs were used frequently.

Both instructional and assessment elements could be included on each page. Many of the pages included an assessment question that the student had to answer to move to the next page. Each of these questions included immediate feedback on the accuracy of the response. These questions provided some formative assessment as the students progressed through the lesson content. Not all pages required the students to answer a question to move on. Each lesson had approximately three of these navigation questions.

Lesson content included text, images, graphs and multimedia. Several animations and videos were included in the physiology lessons. The videos were clearly identified in subtext boxes. Participants were required to click on the link to view any animation or video. Additional text resource was available to supplement the lesson material. Permission was granted to use sections of text from *Human Physiology: An Integrated approach* (Silverthorn, 2006). These subsections were presented as resource web pages that could be accessed through a hyperlink making them immediately available to students who opted to read more about a topic.

An additional level of formative assessment was provided with the Quiz activity in Moodle™. After completing each lesson, the participants were directed to complete the lesson review questions. The review questions incorporated various question types: multiple choice, matching, embedded answer, short answer and true/false. Because this assessment was intended to provide formative feedback, the quizzes were structured to allow the participant more than one attempt at the questions as well as to provide immediate feedback to both correct and incorrect responses.

Summative assessment was completed with a seven question multiple choice pre-test that students would complete prior to opening the first lesson. These questions addressed each of the seven learning general learning objectives for the physiology content. Isomorphs of the assessment questions were developed and grouped together as a post-test that was made available to students after they completed the final physiology lesson and set of review questions.

The data from the pre/post assessments, review questions, and navigation questions in the lessons were collected. Additionally, the Moodle™ activity log provided information about how the participant interacted with the course material. This record along with the Moodle activity report provided information about which videos, animations and extra text readings were accessed. The length of time a student had the specific lesson pages or review questions open on their computer system was also available.

4.2.2 Biofluids challenge modules – data collection environment

The physiology modules were designed to provide study participants with sufficient prerequisite background to support future learning when they encountered subsequent topics in biomedical engineering challenge. To assess the effectiveness of the physiology training, the challenge-based learning model was used to create a second course module using the Moodle™ course management system.

Study participants were asked to collaborate in groups on a challenge-based question related to biofluids (Figure 4-2). Two modules were developed around two challenge questions: Giraffe Hemodynamics and Deep Diving. To solve the challenge, participants needed to draw upon their recently acquired physiology knowledge. Each challenge module was similar in design and focused on the same biofluids learning objectives. The challenge question and some supporting lesson material varied in the two biofluids challenge modules. However, they were designed to be similar enough that the same physiology prerequisite knowledge applied and the same biofluids engineering pre/post assessment could be used.

The purpose of the challenge-based learning modules was to create an environment where it was possible to observe how the students used their new physiology knowledge and collect data related to the adaptive expertise construct. The challenge learning module was developed following the learning and design principles of the STAR.Legacy cycle (Klein & Harris, 2007; Schwartz et al., 1999). The SL Cycle is based on three general principles of instruction. First, knowledge should be presented in context. Second, students should be given opportunities to generate ideas and demonstrate what they know. Third, multiple contexts should envelop the knowledge. Online activities that matched each of the stages of the cycle were set up using both Moodle™ and the Second Life® multi-user virtual environment.

The Moodle™ course management system allowed much flexibility in presenting the elements of the SL cycle. The challenge is presented in an initial topic in the online learning module. When the participants first accessed the Moodle™ course page, the only activities visible were the challenge description and the links that redirected them to the physiology learning modules.

When the students completed the physiology training, they returned to the biofluids challenge Moodle™ page where all of the study learning activities were now accessible to them. Using the topic blocks on the course page as a navigation tool the participants were guided through the stages of the SL cycle (see Table 4-6). With the exception of the synchronous team meetings, all of the learning activities were contained on the Moodle™ course page. Moodle™ quiz and lesson activities were used to present the content. An extensive resource library of research articles and reference material was included as links to files. For asynchronous communication with both peers and a subject matter expert, a discussion forum was available. Finally, a wiki framework was put in place for the participants to use to develop their final solution.

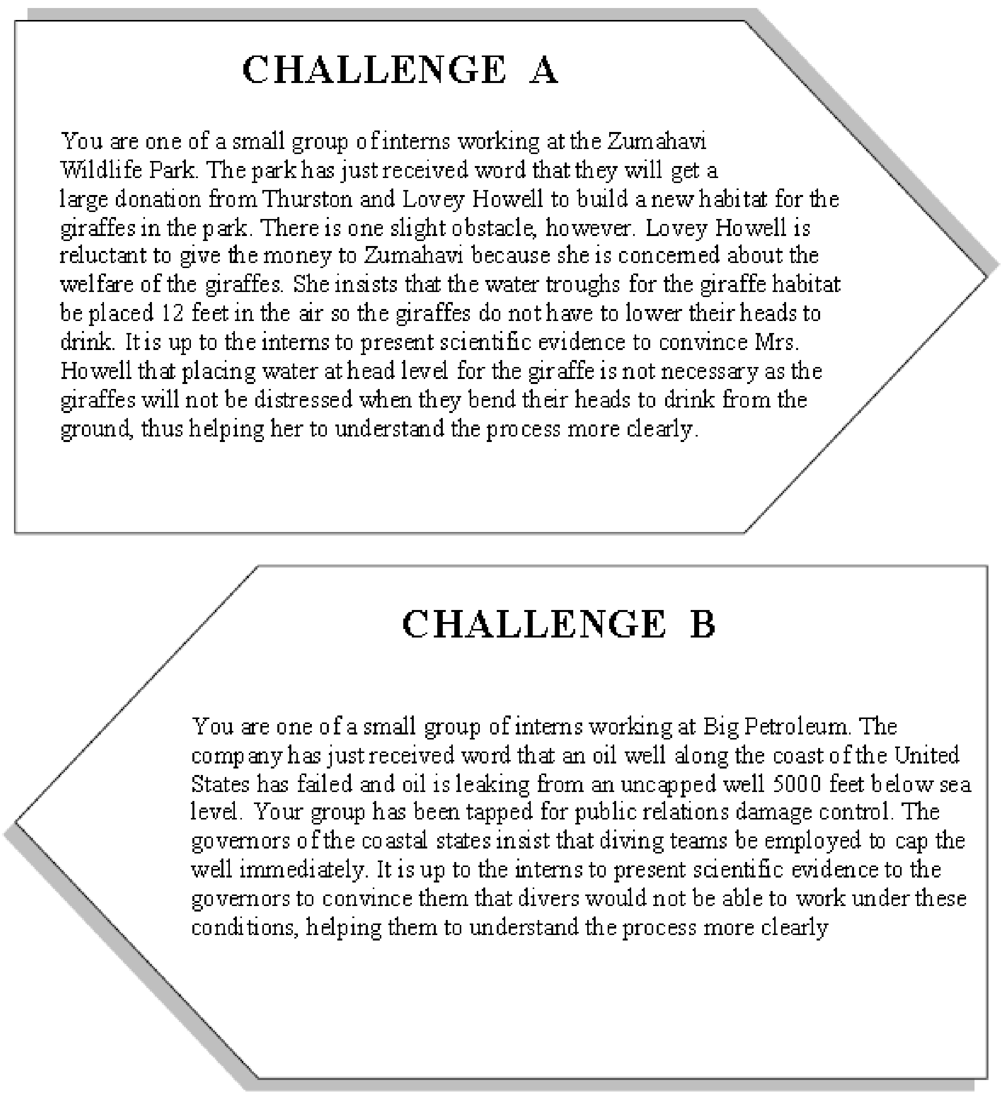


Figure 4-2. Challenge A: Giraffe hemodynamics and Challenge B: Deep diving challenge problems presented to study participants to begin the inquiry-driven instruction process of the SL cycle

Table 4-6. Biofluids challenge module learning activities associated with each stage of the SL cycle.

The Challenge	Giraffe and Diving challenges set up as a role-playing simulation for students
Generate Ideas	Initial thoughts questionnaire Brainstorming meeting in Second Life®
Multiple Perspectives	Fia Baily, subject matter expert (discussion forum) Resource library
Research and Revise	Biofluids lessons Resource library
Test Your Mettle	Peer discussion (discussion forum) Peer discussion (wrap-up meeting in Second Life®)
Go Public	Final solution proposal (wiki)

4.2.3 Second Life Multi-user virtual environment

An important aspect of the challenge-based learning activity was collaborative knowledge construction and generation of a solution. To add a gaming element to the role-play, each participant was assigned an avatar identity when they enrolled in the study. Approximately 200 avatars were created and documented in Second Life®. Participants could select an identity to use in the study from this collection. Further, to ensure the privacy of the study participants, in addition to the avatar identities, a unique email address was established for each participant and setup to forward messages to their personal email accounts. Email addresses for each avatar were created on server space purchased for the study (wiscadademy.com). After the participant chose their avatar in the introductory meeting with the researcher, the remainder of the study interaction was completed with that avatar name.

A vehicle for synchronous communication was provided in the form of a virtual conference room created in the Second Life® multi-user virtual environment (Figure 4-3). Space in Second Life® was leased ($100/year) from the New Media Consortium (NMC, 2009). Using available block elements purchased in the virtual environment and some programming of unique elements, a replica of a conference room was created. Participants were able to log into Second Life® and immediately access the conference room. They were able to walk around the space, chat with others in the room, sit around the table and discuss the challenge, and even purchase a soda from a vending machine. The chat transcript for each meeting was recorded and made accessible for later review by study participants.

Two avatar identities were created and used by the researcher to interact with the participants in Second Life® and the Moodle™ study environment. *Fia Baily* was an avatar created as a subject matter expert. She was introduced to the participants as a resource they could contact as they were developing their solution. She could be approached through the discussion forum where the students could direct any question to her. Additionally, a second avatar, *Adriel Breen*, was created and introduced as a peer facilitator. He was not introduced as an expert or instructor, but had a role to facilitate the two Second Life® meetings for each group. Through this identity, the researcher used a Doodle® poll to schedule the synchronous meetings in Second Life® and send reminders to the participants. During the meetings, *Adriel Breen* called the meeting to order and set the stage by establishing the purpose. After the introduction, *Adriel Breen* assumed an observation role. The peer facilitator did not contribute to the solution. He only answered process questions to guide the participants through aspects of the study (e.g. explain that the wiki was where the final solution would be written *or* remind students to complete the biofluids lessons before the next meeting).

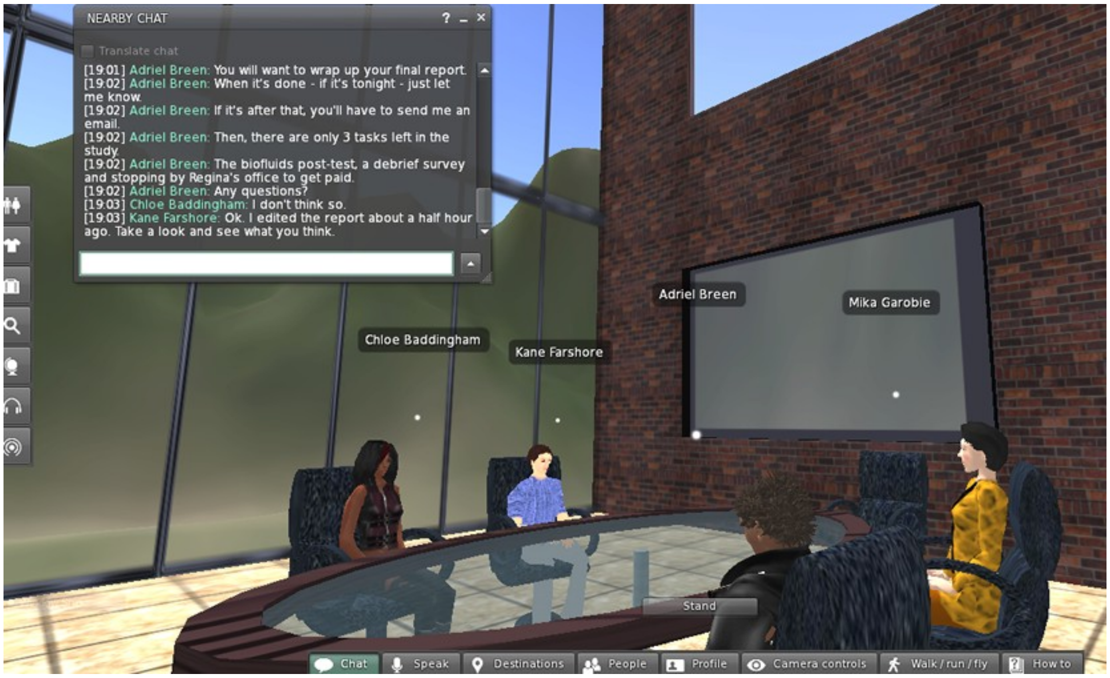


Figure 4-3. Screen capture image of team meeting in Second Life® conference room

4.2.4 Beta test of instrumentation – proof of concept

After the Second Life® conference room was created in the virtual environment, a proof of concept test was conducted to determine if it would be an effective replacement for face-to-face discussions and meet the needs of the study. With approval of the UW-Madison Institutional Review Board (IRB), the Second Life® environment and an initial iteration of the physiology and biofluids challenge modules were tested under Protocol SE-2008-0297 (see Appendix H for IRB protocol).

In Fall 2010, six physiology students who were enrolled in Physiology 335 completed the Beta test protocol. After recruitment and cohort assignment, the participants met with the researcher to complete the informed consent process, receive instructions on how to access the online modules and virtual conference room, and select their avatar.

The participants were asked to test certain aspects of the Moodle™ course modules and Second Life® conference room and provide feedback on accessibility and ease of use. Each participant was asked to read the challenge question and complete two of the physiology lessons. Because the students were taking an on-campus physiology course, they were asked to indicate how long it took them to complete the lessons and rate the order of effectiveness of the extra resource material in each lesson. Additionally, the participants were divided into two groups who met online in the virtual environment to brainstorm a solution to the challenge question. The participants (using their avatars) sat at a virtual conference table and talked with each other using the chat tools. The researcher used the *Fia Baily* avatar to both facilitate this meeting and answer any subject-related questions the participants had. The chat transcript was recorded and evaluated. Additionally, the participants completed a questionnaire about their experience with the Moodle™ learning modules.

Before the Second Life® conference room could be tested, it was apparent that a different scheduling protocol was needed. Only two of the three participants showed up at each of the brainstorming meetings. To test the environment, the *Adriel Breen* avatar was used in the role-playing scenario as an additional intern collaborating on the challenge. Once the participants logged into the meeting at the appropriate time, the results of the Proof of Concept test indicated that the infrastructure of the Second Life® conference room was effective for synchronous meetings. A review of the chat transcript indicated that participants would need some additional assistance in transitioning to the brainstorming activity that was the purpose for meeting. The Second Life® meeting was the first and only time these participants would interact. Although they were meeting with the same purpose, there was no opportunity to establish social roles in the meeting. An effective and efficient (30 minute) meeting required someone to take the lead and start the discussion. When *Fia Baily*, an authority figure, was the meeting facilitator who sat at the conference table with the students, they may have been hesitant to brainstorm freely. The transcript indicated that the study participants did not ask *Fia Baily* any direct questions related to the subject matter, so this facilitation role did not need to be filled by a subject matter expert.

The results from the questionnaires associated with the Moodle™ course pages were consistent. The participant interaction time with the lessons ranged from 30 to 90 minutes. Although this time was likely increased because they were evaluating the lessons, the projected time to complete the lessons was longer than expected. The physiology training modules for the Proof of Concept test included additional review activities using an online shared learning resource (Quia, 2009). These activities included matching exercises and quiz questions that were used as formative assessment. Participants indicated that they were some of the least effective activities in the modules. Some participants had difficulty logging into this outside resource. Several participants indicated that there was too much text on each page. Additionally, the video and flash animations were cited as effective resources by several participants.

Based on the results of the Proof of Concept test, several changes were made to the physiology training modules and the study protocol. To improve the attendance and efficiency of the meetings in Second Life®, the *Adriel Breen* avatar was used as a peer facilitator who scheduled and facilitated all of the group meetings. The online scheduling tool Doodle® was used to find a convenient time for the groups to meet. *Adriel Breen* emailed reminders to increase attendance. It was also important that each participant had confirmed that they could access the Second Life® environment prior to the first meeting. To accomplish this, a pumpkin was placed on top of the Coke® machine in the virtual world. Within 24 hours of the enrollment meeting with the researcher, each participant was instructed to access the Second Life® conference room and email the researcher telling them what they found on top of the Coke® machine. This extra step solved access problems well before the study participant needed to be online for a meeting.

The results of the testing of the Moodle™ course modules led to several changes to the physiology training. The amount of text and other media on each page of the lessons was reduced. Most of the revised pages did not require the students to scroll more than one time to view the entire page of lesson material. In addition to dividing the existing text into two or three pages, redundant and unnecessary content was removed to achieve the goal of lessons that could be completed in approximately 30 minutes. The review activities accessed through the external Quia website were eliminated. The content addressed with these activities was incorporated into additional navigation questions on the new course pages, so the formative assessment component remained.

Observation of how the participants navigated the Moodle™ modules informed the development of a Microsoft Excel spreadsheet to record the data collected from the study. By reviewing the Moodle™ activity reports, it was possible to determine the type of data that could be collected from each of the study activities in both the Second Life® and Moodle™ environments.

4.2.5 Beta test of instrumentation - physiology course modules

After the changes were made to the physiology lessons, the biofluids challenge modules were completed, a final beta test of the modules were conducted. IRB Protocol SE-2008-0297 was modified to allow a second test using engineering undergraduate students to evaluate the revised learning modules.

In Spring 2011, three undergraduate engineering students tested the Moodle™ course pages for the physiology training and biofluids challenge activities. Based on these evaluations, a few additional revisions were made to the Moodle™ course pages. The timing clock was turned off since the information it provided was unnecessary and confusing to the user. Broken links to images and typographical errors were identified and corrected. The participants indicated that there was a good balance between text and images on the lesson pages making them easy to read. The lessons took 30-45 minutes to complete by these participants who were both completing and evaluating each lesson.

After the study participants tested the physiology modules by completing the lessons, the activity reports and activity logs for each of these participants were evaluated. The length of time the participant stated that they needed to complete the lesson was confirmed by viewing the activity logs and activity reports. When the activity report indicated that the lesson time was greater than 30 minutes, the activity log was viewed to confirm that the participant was engaged with the Moodle™ course page for the entire time. Additional data elements were added to the Microsoft Excel spreadsheet including pre/post quiz scores, pre/post quiz engagement times, lesson and review quiz scores, lesson and review quiz engagement times, number of glossary views, and number of learning objective views.

4.3 Quantitative Study Pilot Test

With the Second Life® conference room and Moodle™ course pages Beta-tested, a pilot test was conducted using the Giraffe challenge module and participants assigned to each of the four physiology training modules. An initial IRB protocol (SE-2008-0754) previously approved for the quantitative study was amended to cover testing an additional twelve participants in Fall 2011 as part of a pilot study to finalize the study protocol and data collection plans Appendix I). The original compensation plan for the quantitative study was also amended to pay each participant who completed the pilot study and each who finished the actual quantitative study $100 for their time and effort and increase enrollment.

Six male and six female engineering undergraduate students were initially recruited to test the quantitative study protocol. The participants were assigned as recruited to one of four cohorts who would complete the study together: Anteros, Bacchus, Cerberos and Diomedes. Each group was assigned to complete the physiology training associated with one of the experimental study conditions. All four cohorts were launched within a three-day time span and followed simultaneously by the researcher.

To launch the study, each participant met with the researcher for assignment of an avatar and access credentials for the Moodle™ course pages and Second Life® environment. To collect demographic information, each participant completed an online survey during, or immediately after, this initial meeting. Participants were able to complete the initial study activities on their own by logging on to the Moodle™ course page to read the challenge and begin the seven physiology lessons. All activities were asynchronous in nature until the initial brainstorming meeting. The pilot test uncovered a potential problem of a student not having access to their own Internet-enabled computer. The Moodle™ course pages on the College of Engineering server were accessible from any computer. The Second Life® virtual world required a software program to be installed, so arrangements were made for one of the pilot participants to use a lab computer that had this software. Only one of twelve participants had a problem accessing the Second Life® conference room. A DNS error was incurred when one of the participants attempted to access the conference room. This problem was remedied efficiently and the participant was able to join the meeting.

Two participants did not complete the initial pilot test. These participants were part of the same cohort (Cerberos), so the remaining participant of that group was assigned to complete the study with another cohort. The remaining ten participants completed all activities of the study within five weeks. Since data were not collected for all of the activities in the first wave of the pilot test from one of the experimental physiology conditions, a follow-up group was tested using the same pilot test protocol December 2011-January 2012.

No participant experienced problems with the lessons or review questions for the physiology training and the biofluids challenge. The protocol using *Adriel Breen* as a peer facilitator for the Second Life® meetings was effective. A final protocol was established for this avatar identity to ensure that the same information was provided to each group (Figure 4-4).

The pilot test afforded the first complete test of the biofluids challenge module and challenge-based learning protocol. The Moodle™ course page for the biofluids challenge was designed to help navigate the participant through the stages of the SL cycle. After reading the challenge and completing the prerequisite physiology training, each cohort began to generate ideas about the challenge both independently and collaboratively. The Initial Thoughts Questionnaire (Figure 4-5) guided the participants to begin to think about the challenge and its association with the previous physiology training and the resources available specifically related to the biofluids challenge. The participants completed this activity before they participated in the first collaborative brainstorming meeting. In addition to serving as an advance organizer, the responses to the Initial Thoughts Questionnaire could be compared between experimental physiology training groups.

BRAINSTORMING MEETING PROTOCOL

1. State that you are only here to facilitate.
2. Tell participants three things to get them started:
   - The Zumahavi Board will be looking at your 1 page report for the evidence they will present to Mrs. Howell.
   - Everything you need to help arrive at a solution is contained within the study modules (lessons, resource library, access to a consultant, *Fia Baily*).
   - You can use the discussion forum to communicate with each other or *Fia Baily* in the times between the two online meetings.
3. Help guide a wrap-up to the meeting after the planned 30-minute timeframe has elapsed.

Figure 4-4. Brainstorming meeting protocol followed by the peer facilitator *Adriel Breen*

The study participants had two opportunities to seek multiple perspectives on the challenge question. The brainstorming meeting gave each participant an opportunity to learn what their peers were thinking about the problem. Additionally, participants could ask the subject matter expert, *Fia Baily*, any question about the challenge. *Fia Baily* introduced herself to each participant via a discussion forum post and encouraged the research interns to ask her questions.

To help formulate a solution to the challenge, the participants individually completed four biofluids lessons and had access to an online resource library that contained research articles on the challenge topic. Participants could communicate with each other between the two Second Life® meetings by using the discussion forum. The wiki that the students used to write the final report was available for early drafts at the beginning of the study. Students could use this as a communication vehicle also. During the pilot test, two cohorts used the discussion forum to share findings from the resource library and lessons that contributed to the final solution. One group used the forum to introduce the team to each other, while the other two cohorts did not use the discussion forum. All four of the cohorts that completed the study used the wrap-up meetings in Second Life® to collaboratively draft the final solution report.

INITIAL THOUGHTS QUESTIONNAIRE

1. List the physiology systems and concepts that you predict will be involved in developing a response to Mrs. Howell's concerns.

2. Of the topics you listed above, which will be the three most important for this challenge? (List the most important first)

3. In the Zumahavi Resource Library, information is available on each of the topics below. Select the three (3) topics that you think will be most important in solving the challenge. (Choose at least one answer)
   - Giraffe circulatory system
   - Cerebral hemodynamics
   - Hypertension
   - Syncope
   - Biofluid mechanics in flexible tubes
   - Developmental adaptations to gravity
   - Scaling of mammalian blood pressure

Figure 4-5. Initial Thoughts Questionnaire completed by students individually before meeting as a team to brainstorm ideas for the challenge

After the final report was submitted, each participant was asked to complete a debriefing survey before they met with the researcher to be compensated for their participation. This survey asked the participants to estimate the amount of time they spent participating in the study and which activities they felt were most valuable in developing a solution to the challenge. During the final meeting, each participant was asked if they would be willing to be contacted to participate in a future research study.

The results of the pilot test were used to create the final version of the Microsoft Excel spreadsheet for the quantitative study (Appendix J). The protocol used for the pilot study was effective in guiding the participants through the study and creating observable units in both the Moodle™ course pages and via the transcripts from the Second Life® meetings. It was, however, evident at the conclusion of the pilot study that additional qualitative data would enhance the data that could be collected from the online learning environments. It was determined that four participants would be interviewed extensively by the researcher. The data collected from these interviews would be combined with the record of the learning activities of these four participants as comparative case studies. This list of potential participants for future research created during the exit meetings was used as the sample from which the participants were selected for the qualitative study.

4.4 Qualitative Study Pilot Test

A final IRB protocol SE-2012-0059 was approved for the qualitative pilot test and actual study (Appendix K). The qualitative study would include a qualitative analysis of the participant's learning documents from the Moodle® course management system and the chat transcripts from the Second Life® meetings. In addition to this previously collected data, a structured interview questionnaire was drafted to gather information about how the participants engaged with the study activities their reflections upon how they learn, in general.

One participant from the quantitative pilot study was recruited to test the interview protocol and questionnaire. The researcher and this female participant met privately for one hour and discussed the previous study and learning. The results of the pilot interview informed some small changes to the interview schedule (see Appendix L for final interview schedule).

Chapter 5 - Facilitating development of online collaborative problem-solving skills

Submitted as: Nelson, R.K. and Chesler, N.C., 2013. Facilitating development of online collaborative problem-solving skills in undergraduate engineering students. *Computer Applications in Engineering Education*.

5.1 Introduction

The number of online and hybrid course offerings in undergraduate engineering curricula is increasing. Whether in response to economic challenges in higher education or increasing student demand for alternative course delivery, engineering programs are responding by creating online learning options and more blended/hybrid courses. In an annual report on online education in the United States, online courses are identified as ones in which 80% or more of the course content is delivered using Internet technologies with no face-to-face meetings. A hybrid or blended course is defined as a course that combines online and face-to-face delivery with a substantial proportion (30-79%) of the content delivered online. Enrollment in online courses has reached an all-time high with 32% of students enrolled in degree-granting post-secondary institutions taking at least one online course (Allen & Seaman, 2013). A meta-analysis of online learning studies suggests that although students taking an online course performed better than those receiving face-to-face instruction, hybrid courses have an even larger advantage relative to traditional face-to-face instruction as they include elements from both types of instruction (Means, Toyama, Murphy, Bakia, & Jones, 2010). Students have also shown a preference for hybrid courses when they are offered by their university (Cavanagh, 2011).

The trend toward online and hybrid courses in higher education poses challenges for faculty. Engineering educators recognize the need to establish best practices for online and hybrid course delivery as colleges and departments push to increase the number of these types of courses. Faculty may need to help students develop their own best practices to increase their ability to be effective online learners (Peercy & Cramer, 2011). The demographic cohort known as the Millennials or Net Generation which encompasses the current traditional age students in higher education (age 18-24) is the most technologically savvy in history (Junco & Mastrodicasa, 2007). These students have used technology to communicate and build social networks most of their lives but may not adequately translate these skills to effective collaboration in the online learning environment, which is a precursor to effective online collaboration in the real work environment.

Engineers in the 21st century are faced with increasing complexity and scale of the problems they address. These modern engineering problems frequently require multidisciplinary teams that span multiple locations. Virtual environments are often used to facilitate these collaborations, taking advantage of advances in information and communication technologies. Thus, the ability to communicate effectively in a virtual environment is a critical skill.

Engineering education programs must prepare students to effectively communicate using technology in virtual environments. In pursuit of a traditional undergraduate degree, students are likely to take one or more online courses. The ability to learn in these courses is a skill that students may need to develop and hone. To solve large and complex problems, engineers must develop an attitude of lifelong learning. Many engineers continue to take postgraduate courses that are delivered as part of online degree programs where the use of online communication tools and effective collaborative problem solving in a virtual environment become necessary skills (National Academy of Engineering, 2004).

The ABET criteria require that accredited undergraduate engineering programs have documented student outcomes that prepare graduates to function on multidisciplinary teams, communicate effectively and identify, formulate and solve engineering problems (ABET Engineering Accreditation Commission, 2012). Challenge-based learning (CBL) is an inductive teaching and learning paradigm that promotes the development of the collaborative problem-solving skills that engineering students must acquire. Inductive methods are based on constructivist learning theory. Piaget's concept of *cognitive constructivism* postulated that humans cannot be given information and be expected to understand and use it. Instead, they must construct or build their own knowledge through experience (Piaget, 1973). Vygotsky introduced the concept of *social constructivism*, which posits that language and interaction with others lead to the co-construction of knowledge (Vygotsky, 1978). In CBL, students working together as a group are guided through a series of steps that prompt them to formulate hypotheses, utilize available resources and develop a solution to the problem or challenge presented (Schwartz et al., 1999). Although inductive methods are more often used with medical school students (Barrows & Tamblyn, 1980; Schmidt, 1983), these methods have been effective in undergraduate engineering courses where students had face-to-face contact with both instructors and peers (Cordray et al., 2009; Martin et al., 2007; Yadav, Subedi, Lundeberg, & Bunting, 2011).

The effectiveness of CBL in online engineering learning environments has not been fully explored. A key feature of challenge-based learning is the collaboration. In online and hybrid courses, all or most of the course is delivered online with no class or group meetings scheduled. Thus, offering a CBL course in an online format changes how students must approach collaborative problem-solving. That is, students must learn how to not only communicate but also collaborate in the online environment.

Course management systems (e.g., Moodle™ or Desire2Learn) provide technology well-suited to independent learning. However, creating an effective equivalent for the collaborative elements of inductive learning methods requires more structure or scaffolding than just using available system tools. Fortunately, many of the technologies found in course management systems align with constructivist pedagogical strategies because they were designed to promote student interaction. Nevertheless, promoting interaction and collaboration among students who do not interact face-to-face can be challenging. Instructors may need to guide students in the development of the collaborative problem-solving skills required of the 21st century engineer (National Academy of Engineering, 2004). In this study, we use an online challenge-based learning environment to evaluate how students use collaborative tools as they work together to solve a problem. We evaluate the effectiveness of three online collaborative spaces and also explore three different types of instructor facilitation in association with each of the collaborative spaces. Student usage and preference data were analyzed to determine the effectiveness of the tools for collaborative problem-solving in challenge-based learning.

After a review of related work, we describe three collaborative problem-solving spaces developed in an online learning environment: 1) an asynchronous online discussion forum; 2) a synchronous avatar-based chat room in a virtual world conference room; and 3) a wiki used to create a shared artifact of the collaborative problem-solving activity. Each of these descriptions includes the methods for instructor facilitation for each space. We conclude with suggestions for the use of online tools for collaborative learning.

5.2 Related work

Ensuring that undergraduate students develop collaborative problem-solving skills is supported by the ABET engineering criteria, particularly Criterion 3 which includes eleven distinct outcomes that graduates should possess. Three of these skills are related to collaborative problem-solving (ABET Engineering Accreditation Commission, 2012):

- an ability to identify, formulate, and solve engineering problems (3e);
- an ability to function on a multidisciplinary team (3d); and
- an ability to communicate effectively (3g).

In engineering curricula, capstone design courses often serve the purpose of teaching collaborative problem-solving skills to students. The opportunity to engage in extensive design and research experiences is delayed until the latter years of the undergraduate experience when students have developed substantial engineering knowledge. In the earlier foundational and laboratory courses, development of these skills is not central since assignments typically follow the specific guidelines of well-designed experiments instead of presenting open-ended problems. One way to provide students early practice with collaborative problem-solving is adopting a curriculum model that sequentially introduces students to open-ended problems and group challenges. Problem-based learning and challenge-based learning methods begin by introducing data in the form of a set of observations, experimental results, a case study or a real-world problem for students to analyze. As students begin the process of analysis and problem-solving, they may recognize that they need more information which is either presented to them directly or discovered through continued research (Prince & Felder, 2006). Because introductory information can be easily presented and gaps in student knowledge filled by providing access to resources, this approach can be used early in the undergraduate curriculum and ultimately strengthen the collaborative problem-solving skills before students reach their capstone courses (Eppes, Milanovic, & Sweitzer, 2012).

The STAR Legacy (SL) cycle provides a framework for developing challenge-based learning activities (Iris Center, 2012; Schwartz et al., 1999). The SL cycle follows an inquiry model that includes the following steps (Figure 5-1):

1. Students are presented with a **challenge** that establishes the need to learn content and master skills to develop a solution.
2. Students **generate ideas** about what they may already know about the challenge and begin to think of ways to resolve the problem. These initial thoughts are documented and students are encouraged to discuss their ideas with others.
3. Multiple **perspectives and resources** are provided to allow students to explore other views and background information that may be useful to solving the challenge.
4. **Assessment** activities give students an opportunity to apply what they know and determine gaps in knowledge that send them back to explore additional perspectives and resources, if needed.
5. Finally, a **wrap-up** activity concludes the cycle with a report or summary that indicates that the challenge has been met and provides the students an opportunity to demonstrate their knowledge and skills.

The SL cycle provides a model of challenge-based learning that has been effectively adapted to curricula in many engineering education disciplines (Cordray et al., 2009; Freeman et al., 2010; Freeman, 2010; Fuentes, Vasquez, & Freeman, 2011; Martin et al., 2007).

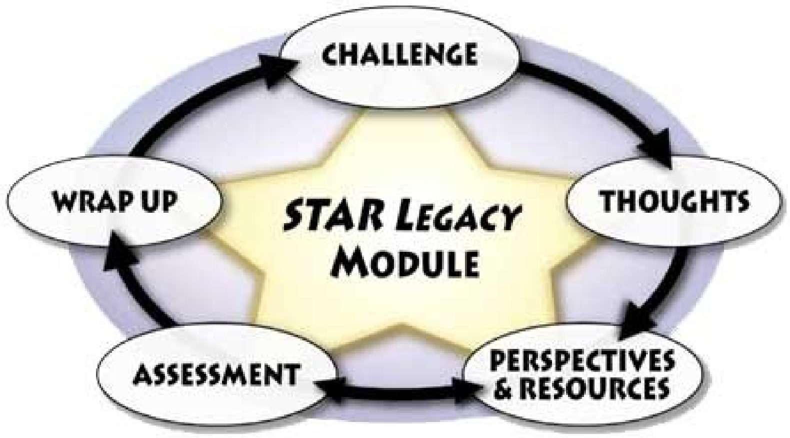


Figure 5-1. The STAR Legacy Cycle used to create online challenge-based learning modules that incorporate collaborative problem-solving. [*Image courtesy of the IRIS Center, Peabody College*]

In small-group challenge-based learning, the *Generate Ideas* step is particularly useful to foster the development of students' collaborative problem-solving skills. During this step students are beginning to determine what information they will need to solve the problem and how they might begin to obtain that information. To facilitate learning, instructors can provide various levels of direction to students as they engage the steps of any inquiry cycle. Martin et al. (2007) examined the effect of providing different prompts to students engaged in generating ideas about the challenge problem. Students who were encouraged to brainstorm what they knew and what they needed to know prior to being given more specific information about the challenge were more flexible in their problem-solving approaches than students who were given the direct instructions without an open brainstorming session.

Communication and critical thinking are hallmarks of effective collaborative problem-solving. Brainstorming activities like those used in the *Generate Ideas* stage of the SL cycle help students to develop communication skills by providing a space to practice articulation of ideas before sharing them with a more public audience. As they share ideas and provide feedback to each other, students are able to learn from their peers. Additionally, the instructor is available to respond to student inquiries by asking further questions that promote critical thinking (Sibley & Parmelee, 2008).

Fostering effective collaborative problem-solving in online learning environments requires consideration of both pedagogical principles and information and communication technologies. There must be a space for the co-construction of knowledge. Students must have the ability to communicate with each other as well as with their instructor. Additionally, technologies should be employed to track student progress and provide instructor feedback.

Creating a space for co-construction of knowledge should occur in two dimensions: a situated space, or reason for students to collaborate, and a physical or virtual space where collaboration can occur. Situated scenarios are designed to present a problem to learners by providing the details needed to begin the problem-solving process. Students should have sufficient prior knowledge and access to any new information they may need as they analyze and solve the problem. When role-playing was incorporated into a situated scenario using online discussion-based collaboration activities (i.e., students were assigned the roles of different employees at a company), the discussion was more focused on the problem-solving task and the responses provided by the students were more diverse than when no roles were assigned (Hou, 2011).

A shared artifact is often the deliverable associated with collaborative problem-solving. Shared artifacts can be group-selected responses to multiple-choice questions (Valdivia & Nussbaum, 2009) or responses that require a more detailed solution that can be quickly scored and ranked (Regueras, Verdu, Verdu, & Castro, 2011). Many artifacts involve some form of collaborative reporting. Workspaces for collaborative reporting can be designed and developed for specific problem-solving activities (Redondo & Bravo, 2006); however, more general collaborative reporting tools can be easily adapted and are freely available on the Internet.

Second generation web technologies (commonly referred to as Web 2.0) provide dynamic tools that let users create online spaces that facilitate social interaction and active engagement (Murugesan, 2007). Blogs and wikis are examples of these dynamic tools. Blogs are two-way communication tools where one or multiple authors share their ideas in an effort to promote feedback in the form of discussion or comments on those ideas. The original blog post and comments become instant records on the Internet. A wiki is a content-management system that allows collaborators to create and edit content through a Web browser. Wikis feature simple site structure and navigation, templates, support for multiple-users and a built-in search function (Murugesan, 2007). Wikis have the potential to enhance student problem-solving collaboration efforts, but may not always reach that potential. Witney and Smallbone (2011) found that students may *co-operate* more than they *collaborate* on group problem-solving tasks using wikis. The wiki effectively provides a structure for developing a collaborative document; however, students lack the skills to work collaboratively to this goal, particularly when the environment moves from face-to-face to a virtual presence.

Asynchronous communication in online learning environments often occurs in the form of discussion forums. Course management systems universally incorporate technologies to provide a computer-mediated discussion forum that can be used to post comments and replies to an initial posting. Effective discussions in these forums require some degree of facilitation by the instructor to encourage students to take an active role in the process. Students also have a direct influence on the effectiveness of online discussion forums as a collaborative tool. Group discussions with dominant members have been shown to be particularly successful. In an asynchronous discussion thread, verbose team members are not “cut off” as might happen in a synchronous discussion. The same study showed that the more information the group shares, the more likely they are to have the relevant information available to effectively create a solution. Peer-sharing of information was effective, but the same was not true with information shared by the instructor. None of the information the instructor posted to the discussion (e.g., offering information about the assignment, the procedure or direction of the discussion) led to any direct difference between the final answers of each group. However, the lack of a direct effect does not countermand the possibility of an indirect effect (Dixson, Kuhlhorst, & Reiff, 2006).

Synchronous communication also occurs in online learning environments, but these communication opportunities require additional organization and planning. Virtual engineering internships, which are simulations of authentic engineering practices, have been developed that require team-based problem solving in an online environment and these utilize both synchronous (chat) and asynchronous (email) communication (Chesler, Arastoopour, D’Angelo, Bagley, & Shaffer, In Press, 2013). However, these simulations required the development of custom code and website development that would be prohibitively expensive (in terms of both time and other resources) for most instructors. Koschmann et al. describe their methods for mediating problem-based learning through a textual chat interface using the off-the-shelf computer-mediated-communication software package NetMeeting™ (Koschmann et al., 2005). In the highly mediated synchronous forum, a high degree of guidance was needed to foster the interest, involvement and support of the group members to elevate a problem from idiosyncratic understanding to understanding by the group as a whole. The students tended to refer to an instructor or tutor to enhance understanding. Moving students to higher levels of collaboration in problem-solving may require making them accountable for evaluating their own responses and working problems out for themselves instead of relying on instructor prompts or tutorial guides (Koschmann et al., 2005).

Studies have shown that virtual worlds support the needs of constructivist learning environments like challenge-based learning (Dickey, 2003; Rudra, Jaeger, Aitken, Chang, & Helgheim, 2011; Vosinakis, Koutsabasis, & Zaharias, 2011). Virtual worlds are three-dimensional (3D) computer-generated spaces where multiple users can navigate, interact and communicate in the virtual body of a 3D avatar. With problem-based learning in a virtual world, traditional face-to-face classroom activities are transferred to the 3D world where avatars can use either text or voice communication in real time.

Vosinakis et al. evaluated a problem-based learning activity carried out in a virtual world they created in the OpenSimulator platform. The virtual environment supported text and voice chat. The collaborative space also had objects that linked to external web resources, objects that contained written messages created by group members, and a tool to record and playback user messages. Students were motivated by the shared space and the aspects of the virtual world that promoted collaborative problem-solving. Additionally, students found the experience fun and engaging (Vosinakis et al., 2011).

Using a different virtual world platform called Second Life®, Rudra et al. (2011) introduced a team-based role-playing activity to teach business concepts. Second Life® is a virtual world where users create avatars that navigate existing 3D spaces and communicate using voice or chat. Since virtual worlds can be created to resemble real-life environments, like an executive meeting room, they are well-suited to role-play scenarios.

In an online instructional environment, a collaborative space and system for communication are not the only factors that should be considered. Effective instruction requires a way to track and assess student progress and provide appropriate feedback. Collaborative online learning environments created using course management systems have these technologies readily available. Based on evidence that online learning groups need some degree of scaffolding and support in the development of collaborative process skills, monitoring group interaction and providing feedback could be an effective instructional strategy (Zumbach, Reimann, & Koch, 2006). Process mining techniques have also been used to analyze formative assessments and learner control in inquiry-driven learning. These tools allow engineering education researchers to examine large amounts of learner data; however, the ability to connect meaning to observed behaviors is limited by the diversity inherent in learners and the process of learning (Howard, Johnson, & Neitzel, 2010).

5.3 Designing collaborative spaces in an online challenge-based learning environment

In this study, a CBL environment was designed to allow undergraduate engineering students to collaboratively solve a challenge question over the course of a 3-week instructional unit. The SL cycle guided the design of a learning environment that was created using the Moodle™ course management system and the Second Life® virtual world platform. Moodle™ is a collection of activity modules that includes Web 2.0 technologies for instructors to develop learning activities like lessons, discussion forums, wikis, and online quizzes.

Using Moodle™, a dynamic web page was created to guide students through the steps of the SL cycle. The ability to selectively reveal resources and activities on the dynamic course page provided a tool to focus student attention. For this CBL unit, it was important for students to read the challenge problem, and then complete a series of physiology lessons before beginning to work together. To direct student focus, only the first two topic sections of the course page were visible to the students until they finished physiology training (Figure 5-2). The physiology training lessons were a way to provide prerequisite content to support the collaborative problem-solving efforts. The collaborative problem-solving element of the CBL unit was initiated by situating the students as a group of research interns in a role-playing scenario (see Figure 5-2 for an example). Three collaborative spaces were provided for the students to work together to solve the challenge: an online discussion forum, a virtual world meeting space for avatar-based chat and a wiki to collaboratively report the final shared artifact.

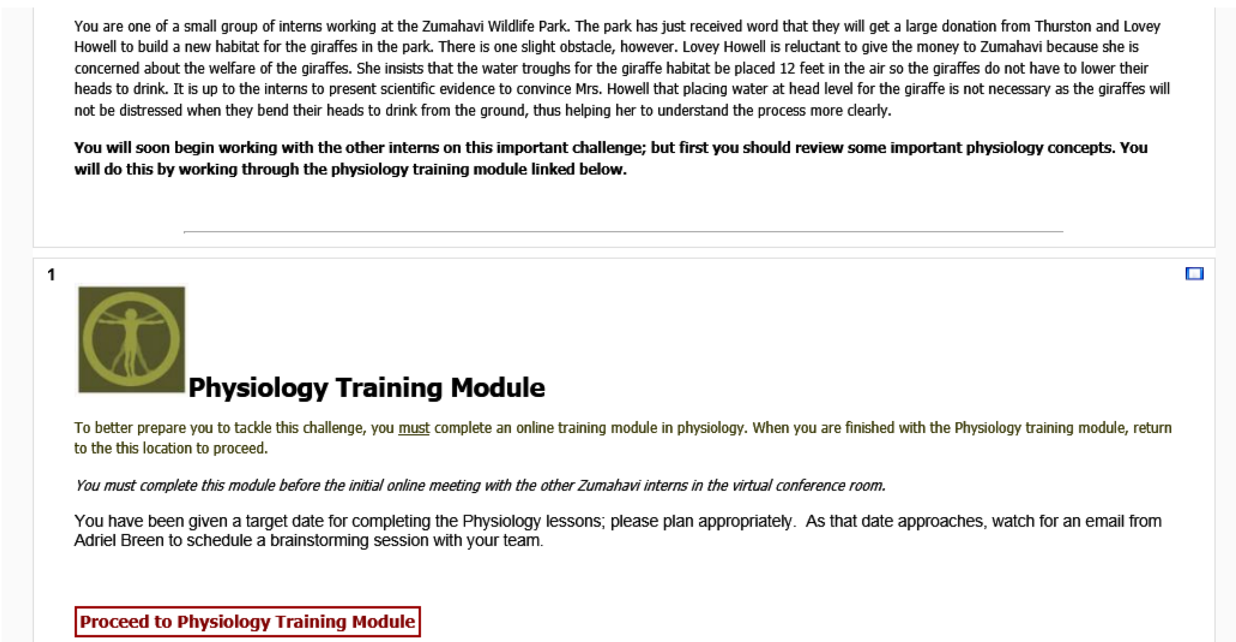
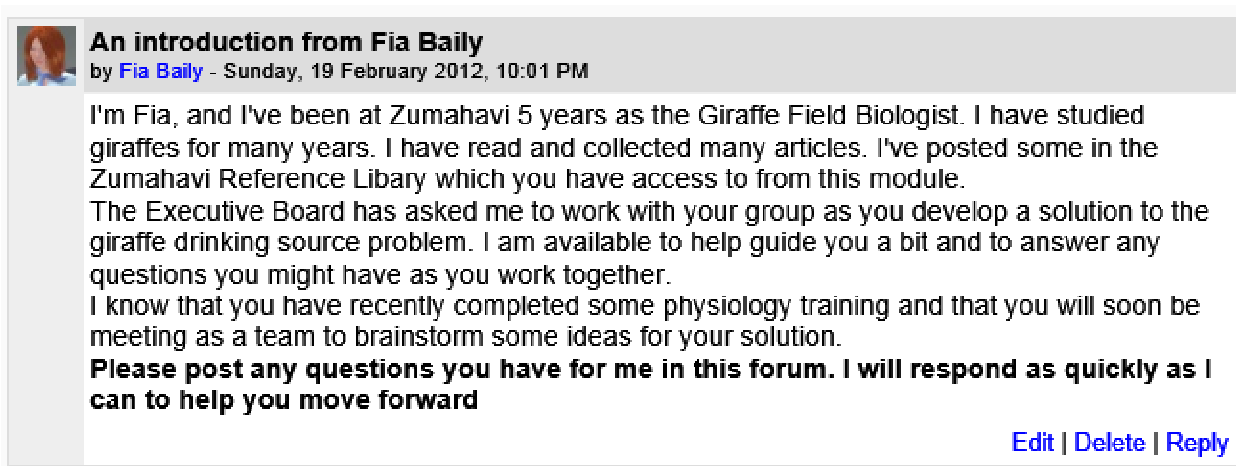


Figure 5-2. Introductory topics on Moodle™ course page used to situate role-playing scenario and direct students to physiology training modules.

5.3.1 Discussion forum

The Moodle™ discussion forum activity was established for asynchronous collaboration. To facilitate collaboration in the discussion forum, the instructor introduced herself to the group members/research interns as a subject matter expert, Fia Baily, and invited them to ask any questions as they worked on the problem-solving activity (Figure 5-3). As part of the role-playing scenario, Fia Baily was the 3D virtual world avatar used by the instructor throughout the activity to provide guidance to the students related to content. Students were encouraged to use the discussion forum to communicate with each other. All posts to the discussion forum were automatically directed to student email accounts.



An introduction from Fia Baily
by Fia Baily - Sunday, 19 February 2012, 10:01 PM

I'm Fia, and I've been at Zumahavi 5 years as the Giraffe Field Biologist. I have studied giraffes for many years. I have read and collected many articles. I've posted some in the Zumahavi Reference Libary which you have access to from this module.
The Executive Board has asked me to work with your group as you develop a solution to the giraffe drinking source problem. I am available to help guide you a bit and to answer any questions you might have as you work together.
I know that you have recently completed some physiology training and that you will soon be meeting as a team to brainstorm some ideas for your solution.
Please post any questions you have for me in this forum. I will respond as quickly as I can to help you move forward

Edit | Delete | Reply

Figure 5-3. The instructor's initial discussion forum post as *Fia Baily* introducing the availability of a subject matter expert to answer content questions related to the challenge question.

In addition to having Fia Baily available as a consultant-on-call, many additional resources were provided on the Moodle™ course page. Research articles related to the challenge question were accessible via hyperlink. Additionally, four online engineering lessons were available to provide students with content knowledge related to biofluidics. These lessons were developed using the Moodle™ lesson activity module.

5.3.2 Avatar-based chat

The extension of the learning environment in the Second Life® virtual world involved the creation of a learning space that included a conference room that could be used for meetings. Through the New Media Consortium (NMC) Virtual World program, educational users of Second Life® can receive services for education and training at discounted rates (New Media Consortium, 2011). For the CBL learning environment, a small plot of land was leased on the NMC campus in Second Life® for US$100/year. The conference room was created in this virtual space and each student was assigned an avatar identity to navigate through the space.

Students met in the avatar-based chat space in Second Life® to begin to collaborate synchronously in a virtual world brainstorming session (Figure 5-4). The instructor utilized a second avatar identity, Adriel Breen, to facilitate the avatar-based chat sessions. Adriel Breen was introduced to the students as a peer facilitator whose role was to facilitate the process of group collaboration. He helped students schedule a meeting time in the virtual world conference room using an online scheduling tool and facilitated the meeting. Since the students only knew each other in the virtual learning environment, Adriel Breen made introductions and started the brainstorming session by framing the purpose of the meeting. At the conclusion of the meetings, he posted the chat transcript on the Moodle™ course page.

5.3.3 Wiki

The final stage of the SL cycle is a wrap-up activity that often includes the presentation of a shared artifact, a summary report that the group develops together. This final shared artifact may take multiple forms, but it is usually some formal documentation or presentation. To support the development of the final report, a third collaborative space was created using a wiki. The wiki was available to the students to begin to use prior to the first brainstorming session. To facilitate use of this collaborative space, the instructions for using the wiki were presented on the Moodle™ course page. Additionally, in his instructions to the students, Adriel Breen encouraged team members to use the wiki to develop their ideas. In the role-play scenario, the report drafted on the wiki represented the final report submitted by the research interns to the stakeholders.

Figure 5-4. Team brainstorming session in the avatar-based chat collaborative space in the Second Life® virtual world facilitated by instructor using Adriel Breen avatar identity.

5.4 Evaluating the online collaborative spaces

An online challenge-based learning environment was created to review how students use the three collaborative problem-solving spaces and their associated instructor facilitation methods: an asynchronous online discussion forum mediated by a subject-matter expert; synchronous avatar-based chat facilitated by an avatar perceived as a peer; and the collaborative wiki reporting space that was facilitated by providing instructions and reminders for use.

5.4.1 Participants and experimental procedures

Forty-eight students were assigned as recruited to sixteen groups of three students who began the online challenge-based learning unit. First and second year undergraduate engineering students at a US research university were recruited via posters in the campus engineering library, announcements at meetings of student organizations and mass email to targeted engineering course rosters. Although the study could be completed at flexible times, participation required a 10 to 12 hour time commitment over a three to four week period. The study was not affiliated directly with any university course. While 48 participants were originally recruited, only 41 completed the study, 25 males and 16 females. To adjust for attrition, the original 16 teams were reduced to 13 with 2 to 4 participants on each team (average team size = 3.16). The study was conducted with approval of the university's Institute Review Board and participants who completed the study were paid US$100.

Before accessing the online learning environments, the participants were asked a survey question related to their enjoyment of problem-solving activities (see Table 5-1). To begin the challenge-based learning, the students were instructed to access the Moodle™ dynamic web page, view the challenge question, and follow the guides on the course page. Eight teams were given a challenge question related to Giraffe Hemodynamics and eight teams explored a Deep Diving challenge question. The experimental process for all of the teams was the same.

Table 5-1. Initial and debriefing survey questions posed to study participants related to problem-solving and the use of online collaborative spaces.

Initial survey question asked of participants prior to beginning the study:

I enjoy the problem-solving aspects of engineering.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*

Debriefing survey questions asked of participants after the study was completed:

Which activities were valuable to some degree in preparing you to solve the challenge? [Check all that apply]	*Physiology training*	*Discussions with team members in Second Life*	*Discussions with team members in Forum*	*Biofluids Lessons*	*Articles in challenge resource library*
Which activity was the most valuable in preparing you to solve the challenge?	*Physiology training*	*Discussions with team members in Second Life*	*Discussions with team members in Forum*	*Biofluids Lessons*	*Articles in challenge resource library*
Given a work situation where face-to-face meetings are not an option, discussion forums are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*
Given a work situation where face-to-face meetings are not an option, wikis are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*
Given a work situation where face-to-face meetings are not an option, meetings in Second Life are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*
Given a work situation where face-to-face meetings are possible, discussion forums are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*
Given a work situation where face-to-face meetings are possible, wikis are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*
Given a work situation where face-to-face meetings are possible, meetings in Second Life are an effective collaboration tool.	*Strongly agree*	*Agree*	*Neither agree or disagree*	*Disagree*	*Strongly Disagree*

Student progress was tracked and when all of the team members had completed the prerequisite physiology training modules, a brainstorming meeting was scheduled in the Second Life® conference room. Each of the 13 teams met in Second Life® for a 30-minute meeting to generate ideas about the challenge problem. Adriel Breen facilitated the brainstorming meetings by starting each meeting with the same scripted information that gave the team some structure related to the collaborative problem-solving process (Figure 5-5). After providing initial instructions and answering any questions the group members had, Adriel Breen let the team interact on their own. He would answer any questions related to the process of the collaborative problem-solving activity, but did not provide any content information related to the challenge question. Additionally, Adriel Breen kept track of the time and helped the team close the meeting after approximately 30 minutes.

[08:05] Adriel Breen: We may as well get started.
[08:05] Adriel Breen: I'm here to help you get started working on a solution to the governor's concerns.
[08:06] Adriel Breen: I'm really only here to facilitate - so I can tell you 3 things.
[08:06] Adriel Breen: 1 - The PR department needs to see a 1 page report of talking points for the governors.
[08:06] Lyric Abbot: Ok, What would those things be?
[08:07] Adriel Breen: 2 - Everything you need to work out a solution will be found in the challenge module. The resource library is available today.
[08:07] Adriel Breen: And 3 - between our two meetings you can communicate with each other or the consultant Fia Baily through the discussion forum.
[08:07] Adriel Breen: Fia should be sending an introductory message today.
[08:08] Adriel Breen: Any questions at this point?
[08:08] Brandi Galaxy: no
[08:08] Lyric Abbot: nope
[08:09] Adriel Breen: I'm going to sit quietly for awhile and let you discuss your initial ideas about the challenge.
[08:09] Adriel Breen: At the end of your discussion I will post your transcript online so you have notes of your meeting.
[08:09] Adriel Breen: My suggestion for starting is to take a quick look at the challenge again.

Figure 5-5. Adriel Breen avatar used by the instructor to facilitate a meeting and the chat transcript from the beginning of a team brainstorming meeting in the Second Life® virtual world.

To facilitate their collaborative problem-solving, in addition to the virtual world meetings, students were provided with two asynchronous online collaboration tools: a discussion forum and a wiki. The online discussion forum was introduced to the students with an introductory post by the instructor using the role of a subject-matter expert, Fia Baily, who indicated that she was available to answer any questions they might have about the challenge problem. The wiki was introduced on the Moodle™ course page with written instructions for how to use it to develop the final report. Additionally, during the brainstorming meeting as part of the process instructions, students were reminded that the wiki was available for them to begin to collaboratively develop their final report. After the students had the opportunity to research and revise their original ideas about the challenge problem, a wrap-up meeting in the virtual conference room was scheduled to allow the group to finalize their collaborative solution and complete the preparation of the final shared artifact. When the students had completed the learning unit, they were asked to respond to a series of questions related to the collaborative spaces as part of a debriefing survey (see Table 5-1).

5.4.2 Results

The students' first opportunity to collaborate was using the discussion forum. After Fia Baily posted the initial message to the discussion forum for each team, only five of the students responded to her by posting in the discussion forum. These five students represented three teams. One student on the *Helios* team used the discussion forum to inform Fia Baily that a link was broken in an article in the resource library. The instructor corrected the link and used the Fia Baily avatar to respond to the student on the forum. Two students on the *Glaucus* team used the discussion forum to share some information that could be used for the final report. Only on the *Concordia* team did a student post in the discussion forum more than one time. Analyzing the three posts in the *Concordia* forum, two posts were used to share information for the final report, and one post included a question specifically directed to fellow team members. The question was never answered by the team members.

Students had two collaborative opportunities in the virtual world conference room: a brainstorming meeting and a wrap-up meeting. Three of the 13 group brainstorming meetings had tardy or absent members. The students who did not arrive in the online conference room for the start of the meeting had previously confirmed their availability and were expected. For the wrap-up meetings, two teams had absent members. One team had two individuals fail to arrive at the Second Life® conference room. In this case the meeting was not rescheduled and the team members used an alternate method to finalize their final report on the wiki. In all of the other cases when a team member did not participate in the meeting, Adriel Breen volunteered to email the participant and direct them to the chat transcript that was posted on the Moodle™ course page immediately after the meeting ended.

Adriel Breen, the peer facilitator, was available to answer process questions. He did not engage in problem-solving with the team members. In the 30-minute meetings, students on average requested explanations from group members over twice as often as they asked Adriel Breen a question. Adriel Breen was asked an average of 2.07 questions per 30-minute meeting. During that same time frame, group members asked a question or requested an explanation from another group member 4.53 times on average.

The wrap-up meetings focused on collaborative development of the final problem solution and the creation of the final shared artifact using the wiki. During the wrap-up meeting, team members were able to access the wiki in real time while chatting with the group in the virtual world conference room.

The transcripts from the team wrap-up meetings were evaluated for indicators of collaborative versus co-operative development of the shared artifact which was the final report wiki. Only four teams collaboratively developed the final report. The members of each of these teams researched areas of the challenge solution and shared their notes either on the wiki, or in one case, in the discussion forum. Then, during the wrap-up meeting each of these groups accessed the wiki and collaboratively organized and edited the document. Each of these four groups submitted their final report at the end of the wrap-up meeting. Eight of the remaining nine teams exclusively used co-operative techniques to complete the final report. In these cases, individuals added their part to the wiki and checked in at the wrap-up meeting to let the team know that they were done. In two of the cases, one team member volunteered to do a quick edit before submitting the final report. One of the co-operative groups did not even meet to talk about the final report; any action that a group member took related to the final wiki was done without any consultation with another group member. The remaining group began to work on their final report collaboratively during the final meeting; however, when they opened the wiki, two members had not finished their parts and were not able to write their sections during the wrap-up meeting. At this point, the group determined that they were not able to finish the document during the meeting and ultimately no collaborative writing was done.

Prior to beginning the challenge-based learning activity, students were asked to respond to the survey statement "I enjoy the problem-solving aspects of engineering" using a 5-point Likert scale. All 41participants indicated that "strongly agree" or "agree" with that statement. After the challenge-based learning activity was complete and the final shared artifact submitted, students were asked their preferences for the three collaborative spaces used in the study. When asked which activities were valuable to some degree in developing a solution to the challenge, 22 students (58%) indicated the discussion with team members in the Second Life® conference room and six students (14%) indicated the discussion forum. When students were asked to choose which activity was the most valuable for developing a solution for the challenge (including the non-collaborative activities which included the physiology training, biofluids lessons, and resource library), only three students (7%) said the avatar-based chat meetings were most valuable and no student indicated that the online discussion forum was most valuable.

In two additional survey questions, students were asked to indicate perceived effectiveness of the three collaborative spaces in work situations where 1) face-to-face meetings were not an option and 2) where face-to-face meetings were possible. When face-to-face meetings were not an option, 22 students (54%) "strongly agreed" or "agreed" that discussion forums could be an effective collaboration tool. Thirty-one students (76%) "strongly agreed" or "agreed" that wikis could be effective; and 25 students (61%) "strongly agreed" or "agreed" that avatar-based chat in a virtual environment could be an effective collaborative tool. However, given a work situation where face-to-face meetings were possible, using the same level of agreement, 18 students (44%) felt discussion forums could be effective, 28 students (68%) indicated wikis could be effective, and only 13 students (32%) agreed that avatar-based chat in a virtual world could be an effective collaboration tool.

5.5 Discussion

Undergraduate engineering programs must prepare students to work with multidisciplinary teams to solve problems (ABET Engineering Accreditation Commission, 2012), which often precludes frequent face-to-face interactions among all team members. The skills required to collaborate with group members in remote locations may soon be taught in engineering courses as the number of online and hybrid courses increase. Instructors adopting online and hybrid course formats will likely use different strategies for facilitating collaboration than they use in a traditional face-to-face setting. In this review of online collaborative learning spaces, we observed that engineering undergraduate students demonstrated different levels of collaboration in the spaces.

Challenge-based learning provides a framework for helping students to develop collaborative skills as they are guided through a cycle of problem-solving activities (Schwartz et al., 1999). While custom online learning environments offer instructors the ability to track, assess and provide feedback to the students as they work together to solve a challenge (Chesler et al., In Press, 2013), these capabilities are also readily available using the Moodle™ course management system. In this study, three online collaborative spaces, each with a different type of instructor facilitation, were creating using Moodle™ and the Second Life® virtual environment.

The discussion forum collaborative space potentially had a high degree of instructor facilitation; however, students had to initiate the request for instructor assistance. The instructor, in the persona of a subject matter expert, was available to answer any student inquiry posed. Each student was told that the subject matter expert was remotely accessible to answer any question at the beginning of the *Generate Ideas* phase of the SL cycle. Even with this access, only one student posed a question to the subject matter expert during the learning experience, and that request was to fix a broken link in the resource library. No students used the subject matter expert as a resource for information related to the challenge problem. Students did not use the discussion forum to communicate with each other even when reminded of its availability. Without student requests for interaction, the discussion forum had very little instructor facilitation. Interestingly, six students indicated that collaboration with peers in the discussion forum was valuable to developing their solution to the challenge. It may be that these students were waiting for a peer to initiate a discussion. Alternatively, it is possible that students did not feel that they had a reason to contact the subject matter expert since they had access to supplementary materials, such as content lessons and an online resource library of subject-matter documents. Moodle™ tracking reports show that all students completed the lessons and over half accessed the resource library documents. The lack of student use of the discussion forum as a collaborative space requires further exploration.

Students exhibited collaborative behaviors in the avatar-based chats. The brainstorming meeting and wrap-up meeting were facilitated by an instructor using the persona of a tutor or peer facilitator, Adriel Breen, who understood the technology and knew the process for completing the online learning activities. Students in all but one of the groups asked Adriel Breen at least one clarifying question related to the development of the final report. In this role, the instructor/facilitator was able to remind the students to use the wiki for collaborative reporting and answer questions on how to use the wiki technology.

Using an online chat facilitator who is perceived by students as a peer may encourage them to ask questions they might not otherwise ask an instructor. Even though Adriel Breen began each team meeting with the same set of instructions, he was asked one to five clarifying questions by group members at all but one brainstorming meeting. Using the peer facilitator was an effective way of providing important instructions in a “just-in-time” manner, particularly at the first group meeting. Although Adriel Breen helped to structure the collaborative process, students collaborated during these sessions by asking and answering each other’s questions.

The avatar-based chat space required that students gather at the same time. The use of this virtual synchronous communication requires more planning than face-to-face synchronous communication that might be incorporated into a traditional face-to-face or hybrid course. Instructor facilitation in the form of the Adriel Breen persona was valuable to helping students schedule team meetings in the Second Life® conference room. This reduced the amount of organization and planning required by the student team members to schedule a meeting. With access to polling web applications, students could schedule their own meetings. However, assigning a facilitator role to a student would increase the efficiency of this part of the online collaborative process (Hou, 2011).

Students were given the instructions for using the wiki to collaboratively write the final report at the beginning of the SL cycle when they were generating ideas. As found previously (Witney & Smallbone, 2011), students did not use the wiki space to its fullest potential. Only four of the 13 teams had members collaborate, as opposed to co-operate. The groups who used a collaborative process to finish the report for the stakeholders followed different steps than the groups who co-operated to write their report on the wiki. The four groups who collaborated followed the same three steps: 1) at the end of the brainstorming meeting, they made research and writing assignments for each group member; 2) team members individually took responsibility to complete their assignments; and 3) when they had the opportunity to work together in the avatar-based chat wrap-up meeting, they talked about how best to edit sections and constructed knowledge together as a team.

Over half of the study participants felt that when face-to-face meetings were not possible all of the collaborative spaces could be effective. Although second to wikis in perceived effectiveness, the facilitated avatar-based chat in the Second Life® virtual conference room was actually the collaborative problem-solving space where participants in this study most often worked together. The discussion forum potentially had the highest level of instructor facilitation, but it was not used by the students, therefore there was little facilitation involved. Instead, the students used the avatar-based chat meetings that were arranged and facilitated by the instructor using an avatar persona that the students recognized as a peer. The collaborative wiki space had the least instructor facilitation. The instructions were posted on the course page and students were reminded to use the wiki to create their final report.

5.6 Conclusions and future work

As the number of online course offerings increases, undergraduate students will be required to develop the skills that allow them to effectively collaborate with their peers in online environments. In addition to learning how to effectively collaborate with peers, online collaboration is made more complex by the need to learn how to effectively use the technologies that enable those interactions. To help engineering students learn to be better collaborative problem-solvers in an online environment, instructors should be prepared to facilitate the use of these technologies. This study presented examples of some types of facilitation that instructors could use when helping students develop collaboration skills in online environments. Undergraduate students in this study collaborated more often in the avatar-based chat space that incorporated a perceived peer facilitator. Students did not use the discussion forum for collaboration even when it was set up to include high levels of instructor facilitation. Future work should explore how students use collaborative spaces they perceive as instructor-facilitated as opposed to spaces they perceive as facilitated by a peer. For engineering students to achieve the required learning outcomes of accredited programs in online and hybrid courses, they will need to be able to effectively collaborate in online spaces.

Chapter 6 –Statistical Analysis of Quantitative Experiment Data

After the pilot tests were completed, undergraduate engineering students were recruited for the quantitative experiment. Data were collected and analyzed to test for effects of physiology content structure and mathematical approach. These two independent variables were manipulated to create four physiology learning modules that presented the same physiology content in four different ways:

- Qualitative, system-based (QLSB)
- Qualitative, concept-based (QLCB)
- Quantitative, system-based (QTSB)
- Qualitative, concept-based (QTCB)

Participants were assigned in groups of three to complete one of the experimental physiology modules. Four groups were assigned to each experimental condition. To test the transfer of physiology knowledge, an online engineering learning environment was created in which the participants could be observed as they used their new knowledge to navigate biomedical engineering topics and collaborate to solve a challenge question. Challenge-based learning modules were developed around two different biofluids challenge questions. Biofluids challenge problem was a third independent variable. Eight groups were assigned to the Giraffe Hemodynamics challenge and eight groups were assigned to the Deep Diving challenge. Other than the question and topic, the learning activities of the two biofluids challenge modules were developed to be nearly identical.

To articulate the research question, four null hypotheses were proposed:

H_{o1}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a quantitative approach and those who were taught via a qualitative approach.

H_{o2}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a system-based approach and those who were taught via a concept-based approach.

H_{o3}: There is no difference in levels of adaptive expertise based on an interaction between mathematical approach and the way that the course content is structured.

Using a 2 x 2 experimental design, the main and interaction effects were analyzed by comparing two performance variables: Adaptive Expertise in Physiology and Biofluids Learning Gain. The components of the Index of Adaptive Expertise were also analyzed: AdEX_Factual, AdEX_Conceptual and AdEX_Transfer.

6.1 Independent variables

The mathematical approach and content structure were manipulated in the design of the physiology training modules completed by the students. Content structure (CS) had two levels: concept-based and system-based. The two levels of Mathematical Approach (MA) were qualitative and quantitative. Two biofluids challenge problems (BCP) were assigned: Giraffe Hemodynamics and Deep Diving. 6.2 Dependent Variables

The Adaptive Expertise in Physiology (AEP) dependent variable was derived using a metric previously used in engineering education research, the Adaptive Expertise Index (AdEX Index). The AdEX Index calculates a single effect size by weighting the results of questions of factual knowledge, conceptual knowledge and the associated transfer questions (Cordray et al., 2009; Pandy et al., 2004). In this study, the factual and conceptual knowledge components were obtained from scores on a pre/post assessment associated with the physiology training. The physiology pre/post assessment consisted of seven questions with one point awarded for each complete answer and partial credit (less than one) awarded for correct answers to parts of multiple part questions. To calculate AEP, the questions on the physiology pre/post assessment were divided into factual knowledge (5 out of 7) and conceptual knowledge (2 out of 7) questions. The transfer component included both the factual and conceptual questions. It was calculated by obtaining a score when the same seven physiology questions were asked once again as a review question in the biofluids engineering challenge module.

In addition to raw scores, student learning gains were calculated using pre/post and post/transfer assessment scores. Factual and conceptual physiology pre/post learning gains were calculated from raw scores on the physiology pre- and post-test assessment (Equation 6-1). The post/transfer learning gain was calculated using the physiology post-test score on all seven (both conceptual and factual) questions and the participant's score on the same physiology questions asked once again as a review question in the biofluids engineering challenge module (Equation 6-2). Adaptive expertise in physiology was calculated using the resultant learning gains (Equation 6-3).

$$\textbf{Physiology Pre/Post Learning Gain} = \frac{\textbf{Physiology Posttest score} - \textbf{Physiology Pretest score}}{7 - \textbf{Physiology Pretest score}} \qquad \textbf{Equation 6-1}$$

$$\textbf{Physiology Post/Transfer Learning Gain} = \frac{\textbf{Physiology Transfer score} - \textbf{Physiology Posttest score}}{7 - \textbf{Physiology Posttest score}} \qquad \textbf{Equation 6-2}$$

$$\begin{aligned}\textbf{AEP} = \{ & (0.1 * \textbf{Factual Physiology Pre/Post Learning Gain}) + \\ & (0.4 * \textbf{Conceptual Physiology Pre/Post Learning Gain}) + \\ & (0.5 * \textbf{Physiology Post/Transfer Learning Gain}) \}\end{aligned} \qquad \textbf{Equation 6-3}$$

A second dependent variable, Biofluids Learning Gain (BLG) was calculated from student pre/post scores on an engineering assessment (Equation 6-4). This assessment measured learning gain related to the engineering concepts presented in the challenge module. The biofluids pre/post assessment had eight questions and students received one point for a correct and complete answer with partial points scored.

$$\textbf{Biofluids Pre/Post Learning Gain} = \frac{\textbf{Biofluids Posttest score} - \textbf{Biofluids Pretest score}}{8 - \textbf{Biofluids Pretest score}} \qquad \textbf{Equation 6-4}$$

6.3 Participants

The study was not affiliated with any university course. First- and second-year undergraduate engineering students at a US research university were recruited via posters in the campus engineering library, announcements at meetings of student organizations and mass email to targeted engineering course rosters. Forty-eight participants were originally recruited and assigned to groups. At the time of the study, all participants had completed or were currently taking their second college-level calculus course and none had taken a college-level or high school advance placement physiology course. The study was conducted with approval of the university's Institute Review Board and participants who completed the study were paid $100.

Participants were assigned as recruited to teams of three students. Eight teams were assigned to the Giraffe Hemodynamics challenge question and eight to the Deep Diving challenge question. Additionally, within each biofluids challenge module, two teams were assigned to each of the four experimental physiology training conditions: QLSB, QLCB, QTSB, and QTCB. Once assigned to a team, each participant met with the researcher in a face-to-face meeting where the general study procedures were explained and login instructions provided. After this meeting, all of the remaining study activities were completed remotely with an Internet connection to the Moodle™ or Second Life® study learning environment. The study protocol is defined in Chapter 4.

6.4 Statistical tests

The data were analyzed as a 2 x 2 experimental design with mathematical approach and content structure of physiology as the independent variables. Mean, standard error of the mean, minimum, maximum and standard deviation were calculated for each variable (AEP and BLG). Skewness and kurtosis, as well as the standard error (SE) for skewness and kurtosis, were calculated to determine appropriate tests for main effect of content structure and mathematical approach.

In addition to skewness and kurtosis data, Levene's Test for Equality of Error Variances was used to determine if the data should be analyzed using parametric or nonparametric tests. Analysis of variance was used to test for significant effects of all data distributed parametrically.

6.5 Results

The pre/post assessments and transfer scores were collected to test the quantitative hypotheses and calculate AEP and BLG. Additionally, the individual components of the Index of Adaptive Expertise were analyzed. The quantitative data were analyzed using descriptive statistics and appropriate comparative tests to test the three hypotheses posed regarding the impact of physiology content structure and mathematical approach on learning. Forty-one participants completed the study, 25 males and 16 females. Although six participants were assigned to each cell, the number who completed the study was less than six in some cells which is reflected in Table 6-1.

TABLE 6-1. Independent variables for experimental design with number of participants

	Content Structure (System-based, Concept-based)	
Mathematical Approach (Qualitative, Quantitative)	Qualitative, System -based n=6	Qualitative, Concept -based n=5
	Quantitative, System -based n=6	Quantitative, Concept -based n=6

GIRAFFE HEMODYNAMICS CHALLENGE

	Content Structure (System -based, Concept -based)	
Mathematical Approach (Qualitative, Quantitative)	Qualitative, System -based n=4	Qualitative, Concept -based n=4
	Quantitative, System -based n=4	Quantitative, Concept -based n=6

DEEP DIVING CHALLENGE

6.5.1 Analyses of Factual, Conceptual and Transfer component scores

The raw AEP component scores for both the Physiology pre-test and post-test were analyzed separately before they were used to determine learning gain scores.

6.5.1.1 Descriptive statistics and Univariate Tests of Factual Pre-test component

Mean, range and standard deviation data are reported in Table 6-2. The skewness and kurtosis data are reported in Table 6-3.

TABLE 6-2. Minimum, maximum, mean, standard error of the mean and standard deviation of the factual component of the physiology pre-test by biofluids challenge problem and physiology training experimental condition

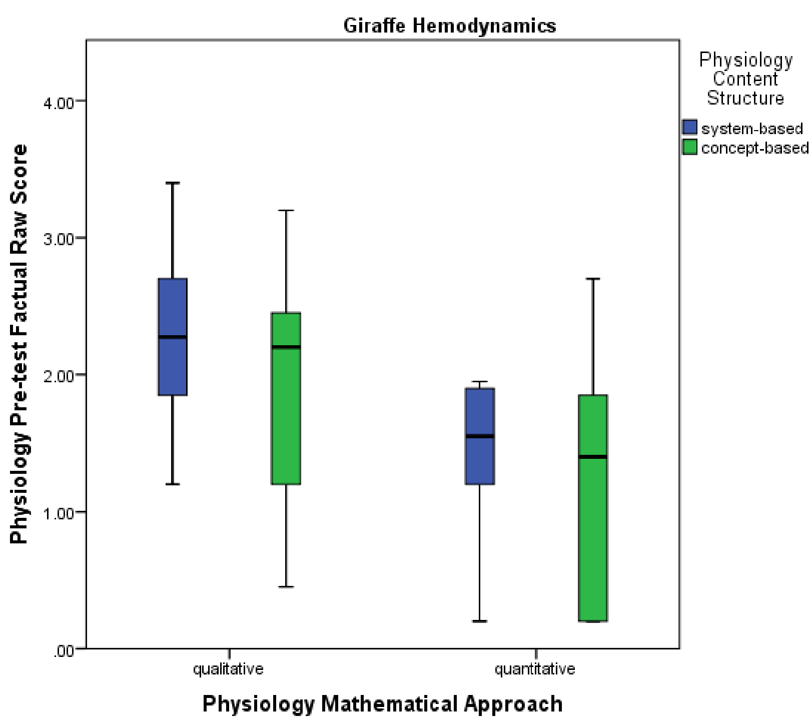
Biofluids Challenge	**Physiology Training (n)**	**Physiology Pre-test Factual Component**				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	1.20	3.40	2.28	.320	.783
	QLCB (5)	.450	3.20	1.90	.483	1.08
	QTSB (6)	.200	1.95	1.39	.264	.648
	QTCB (6)	.200	2.70	1.29	.396	.970
Diving	QLSB (4)	1.20	3.15	2.04	.454	.909
	QLCB (4)	.200	3.40	2.36	.735	1.47
	QTSB (4)	1.40	3.20	2.18	.401	.802
	QTCB (6)	1.45	3.20	2.06	.293	.717

TABLE 6-3. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the factual component of the physiology pre-test by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	.066(.845)	-1.52(.845)
				Kurtosis (SE)	-.586(1.74)	2.45(1.74)
			Concept-based	Skewness (SE)	-.330(.913)	.121(.845)
				Kurtosis (SE)	-1.03(2.00)	-.811(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	.514(1.01)	.667(1.01)
				Kurtosis (SE)	-2.71(2.62)	-1.24(2.62)
			Concept-based	Skewness (SE)	-1.78(1.01)	.956(.845)
				Kurtosis (SE)	3.20(2.62)	-.633(1.74)

Factual pre-test component scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-1). Since the experiment was designed to have no BCP effect, Factual pre-test component scores were plotted by MA and CS (Figure 6-2). Outliers were noted, but not removed from the data set.

A.



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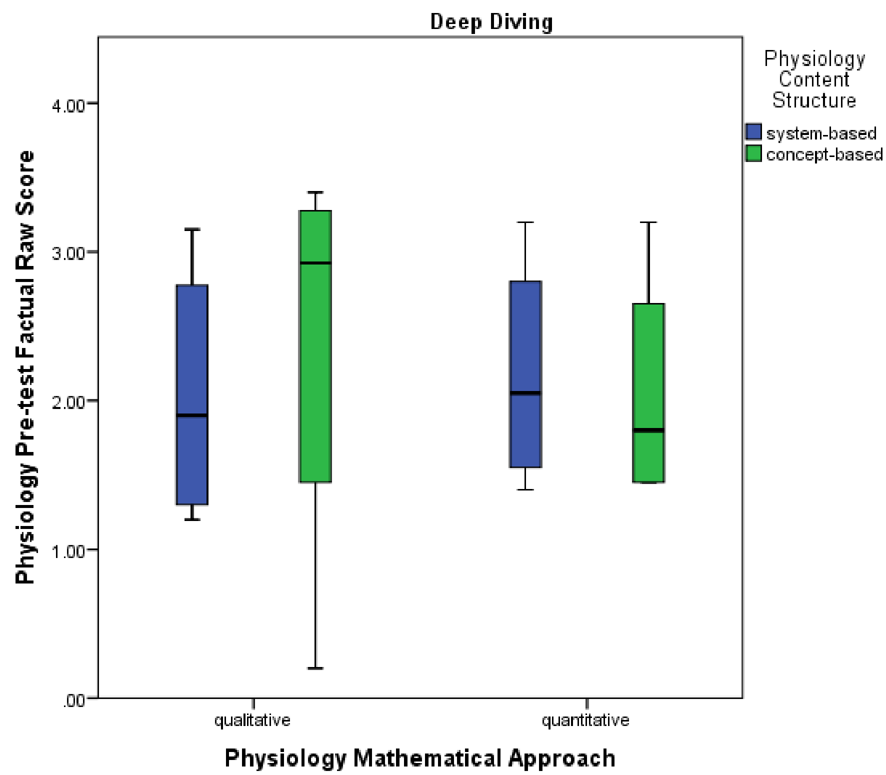


Figure 6-1. A) Factual component of physiology pre-test by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem B) Factual component of physiology pre-test by mathematical approach and physiology content structure for the Deep Diving challenge problem

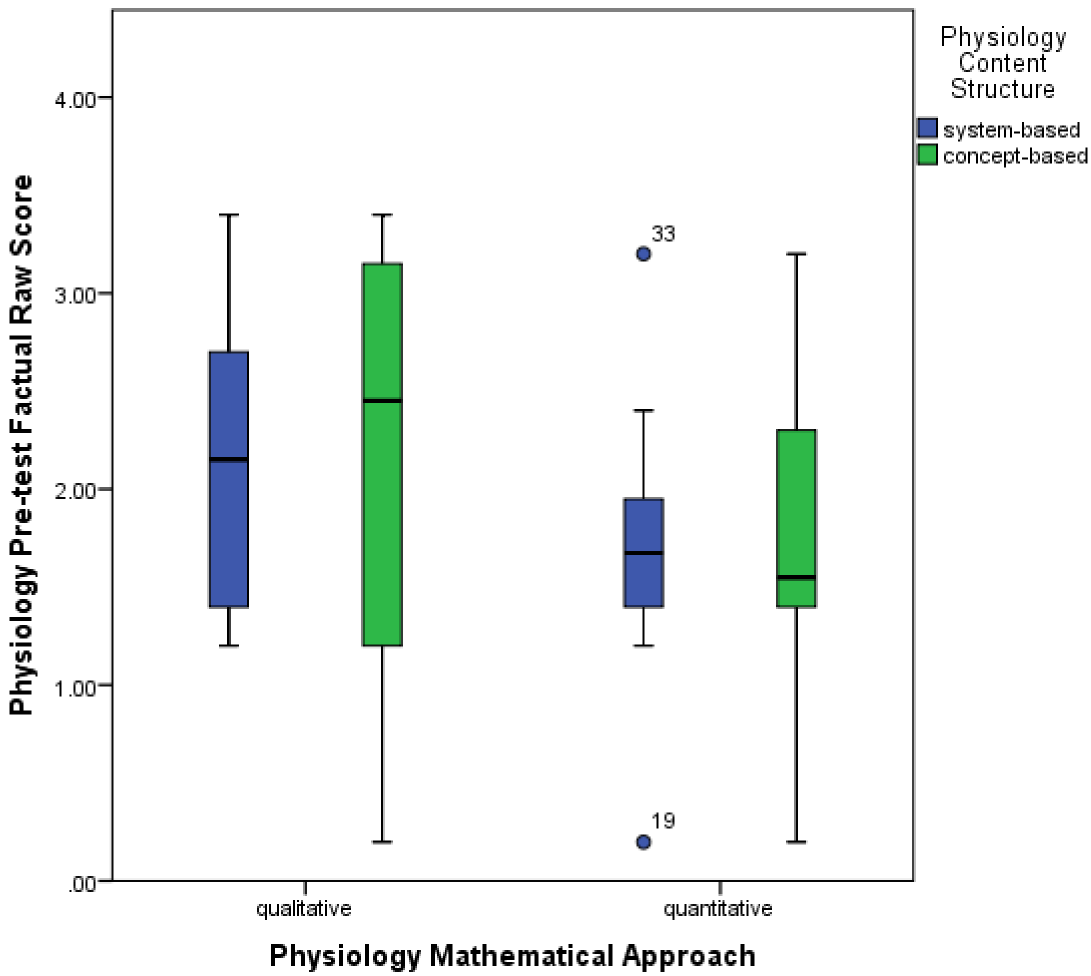


Figure 6-2**.** Factual component of physiology pre-test by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the factual pre-test component scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 1.299$, $p = 0.289$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.035$, $p = 0.852$] or Mathematical Approach [$F(1,37) = 2.441$, $p = 0.127$].

6.5.1.2 Descriptive statistics and Univariate Tests of Factual Post-test component

Mean, range and standard deviation data are reported in Table 6-4. The skewness and kurtosis data are reported in Table 6-5.

TABLE 6-4. Minimum, maximum, mean, standard error of the mean and standard deviation of the factual component of the physiology post-test by biofluids challenge problem and physiology training experimental condition

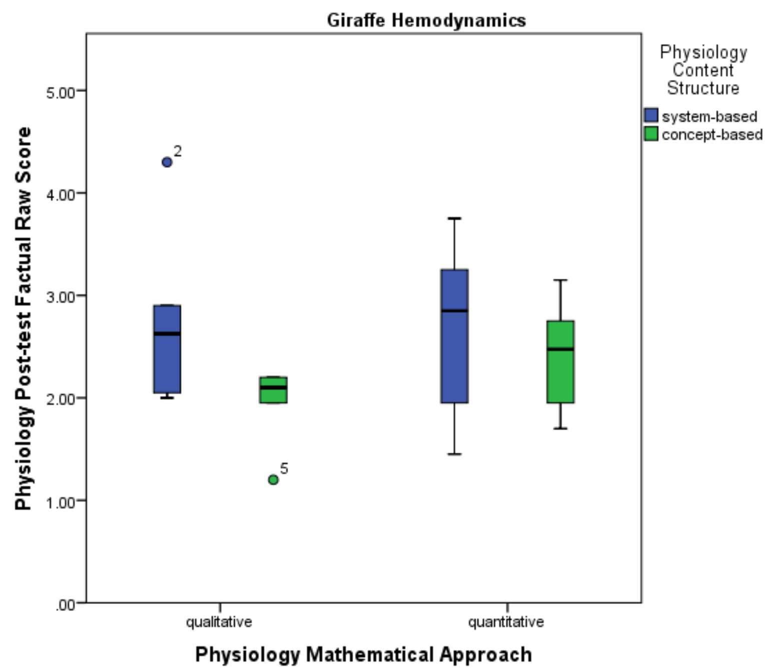
Biofluids Challenge	**Physiology Training (n)**		**Physiology Post-test Factual Component**			
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	2.00	4.30	2.75	.349	.856
	QLCB (5)	1.20	2.20	1.93	.188	.421
	QTSB (6)	1.45	3.75	2.68	.345	.846
	QTCB (6)	1.70	3.15	2.42	.217	.533
Diving	QLSB (4)	.700	4.10	2.38	.795	1.59
	QLCB (4)	1.65	3.55	2.54	.396	.792
	QTSB (4)	1.15	3.65	2.15	.576	1.15
	QTCB (6)	1.05	4.75	2.61	.538	1.32

TABLE 6-5. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the factual component of the physiology post-test by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	1.39(.845)	-.428(.845)
				Kurtosis (SE)	2.05(1.74)	-.779(1.74)
			Concept-based	Skewness (SE)	-1.93(.913)	-.064(.845)
				Kurtosis (SE)	3.79(2.00)	-.909(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	0.49(1.01)	.825(1.01)
				Kurtosis (SE)	-3.93(2.62)	-1.23(2.62)
			Concept-based	Skewness (SE)	.439(1.01)	.605(.845)
				Kurtosis (SE)	.686(2.62)	.436(1.74)

Factual post-test component scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-3). Since the experiment was designed to have no BCP effect, Factual post-test component scores were plotted by MA and CS (Figure 6-4). Outliers were noted, but not removed from the data set.

A.



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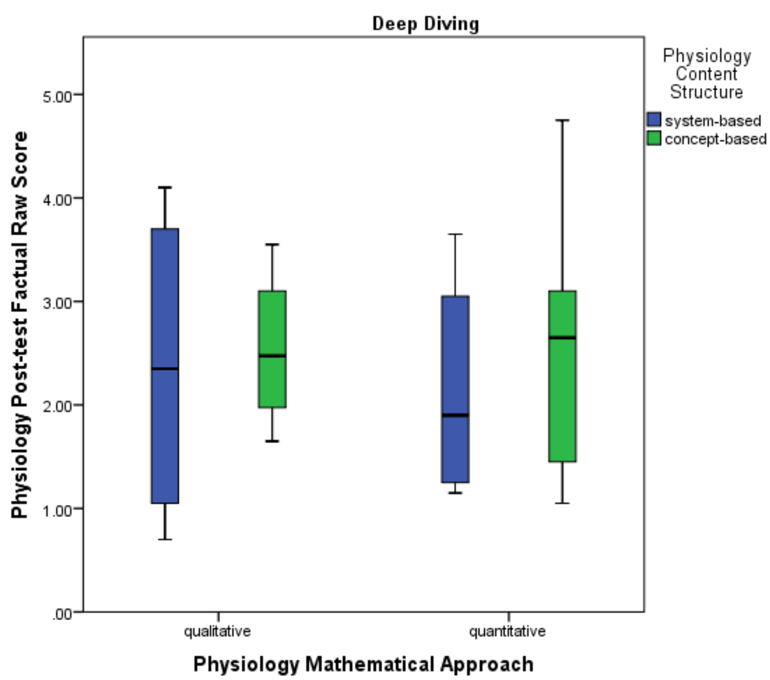


Figure 6-3. A) Factual component of physiology post-test by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem (with outliers noted by participant number) B) Factual component of physiology post-test by mathematical approach and physiology content structure for the Deep Diving challenge problem

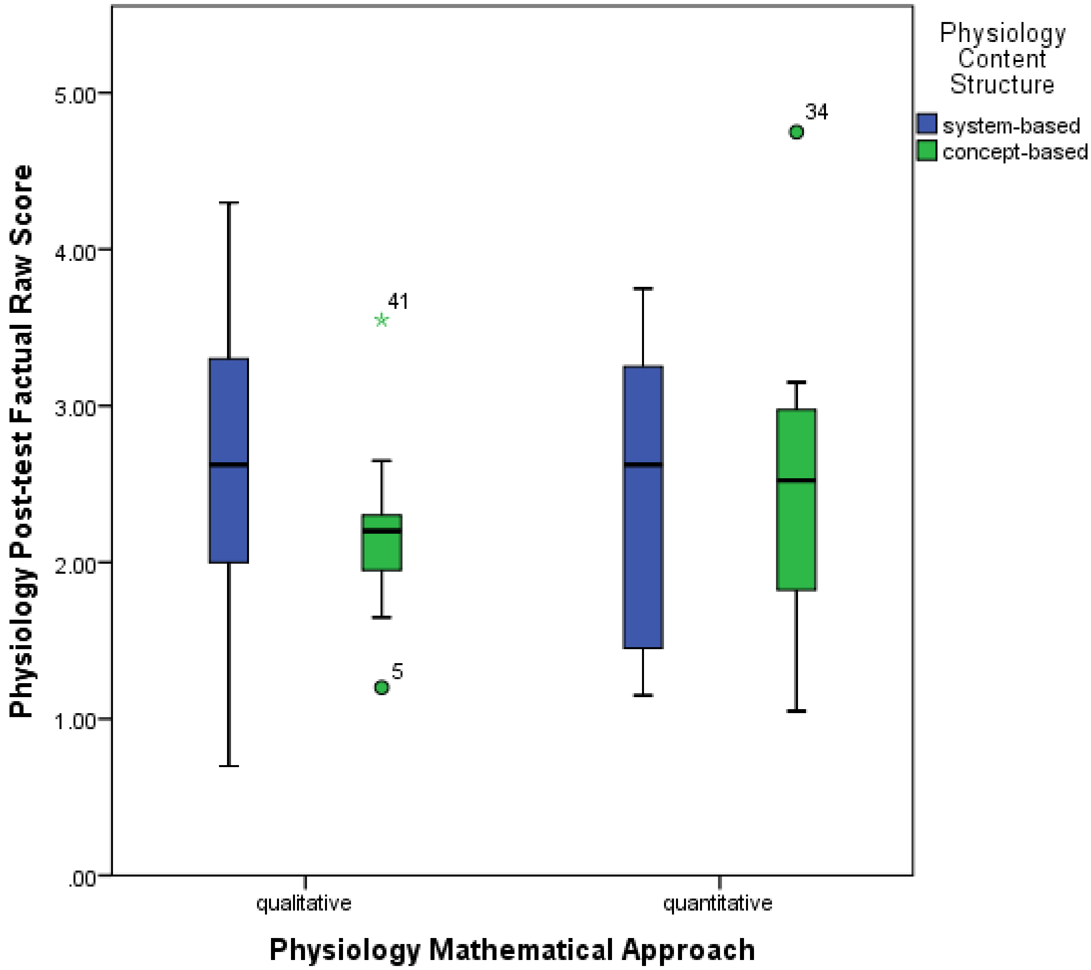


Figure 6-4**.** Factual component of physiology post-test by mathematical approach and physiology content structure with outliers noted by participant number (Participant 41 is an extreme outlier)

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the factual post-test component scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 1.261$, $p = 0.302$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.358$, $p = 0.553$] or Mathematical Approach [$F(1,37) = 0.093$, $p = .762$].

6.5.1.3 Descriptive statistics and Univariate Tests of Conceptual Pre-test component

Mean, range and standard deviation data are reported in Table 6-6. The skewness and kurtosis data are reported in Table 6-7.

TABLE 6-6. Minimum, maximum, mean, standard error of the mean and standard deviation of the conceptual component of the physiology pre-test by biofluids challenge problem and physiology training experimental condition

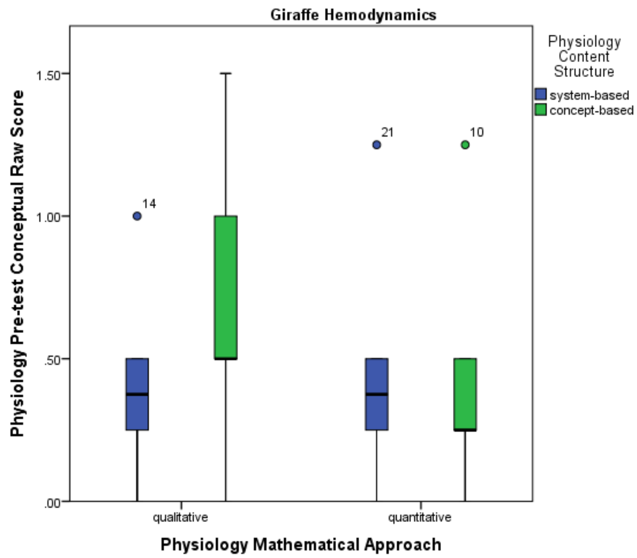
Biofluids Challenge	Physiology Training (n)	Physiology Pre-test Conceptual Component				
		min	max	$\bar{x}$	SEM	σ
Giraffe	QLSB (6)	.000	1.00	.417	.139	.342
	QLCB (5)	.000	1.50	.700	.255	.570
	QTSB (6)	.000	1.25	.458	.176	.431
	QTCB (6)	.000	1.25	.417	.179	.438
Diving	QLSB (4)	.250	1.50	.688	.295	.591
	QLCB (4)	.250	.500	.313	.063	.125
	QTSB (4)	.000	1.00	.500	.204	.408
	QTCB (6)	.000	1.00	.583	.190	.466

TABLE 6-7. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the conceptual component of the physiology pre-test by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	Content Structure	System-based	Skewness (SE)	.889(.845)	1.44(.845)
				Kurtosis (SE)	1.34(1.74)	2.72(1.74)
			Concept-based	Skewness (SE)	.405(.913)	1.76(.845)
				Kurtosis (SE)	-.178(2.00)	3.56(1.74)
	Diving	Content Structure	System-based	Skewness (SE)	1.19(1.01)	.000(1.01)
				Kurtosis (SE)	.436(2.62)	1.50(2.62)
			Concept-based	Skewness (SE)	2.00(1.01)	-.165(.845)
				Kurtosis (SE)	4.00(2.62)	-2.81(1.74)

Conceptual pre-test component scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-5). Since the experiment was designed to have no BCP effect, conceptual pre-test component scores were plotted by MA and CS (Figure 6-6). Outliers were noted, but not removed from the data set.

A.



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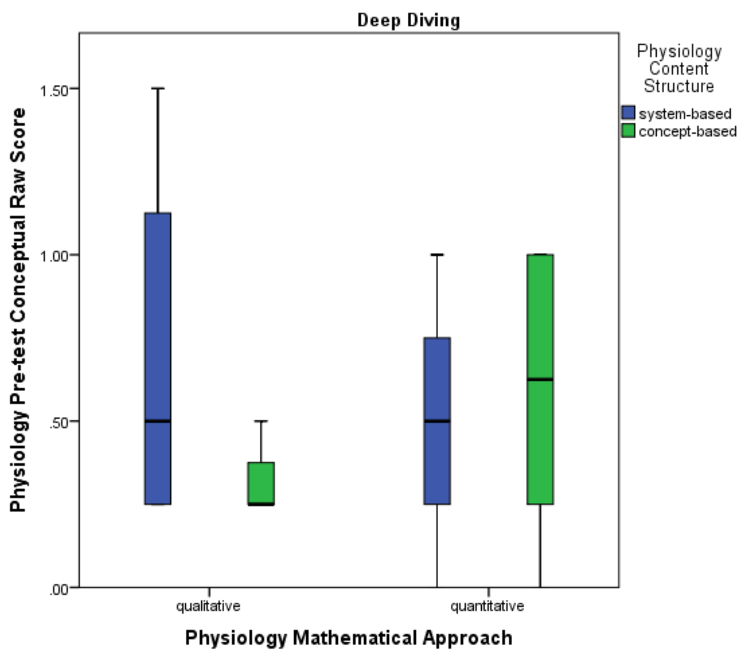


Figure 6-5. A) Conceptual component of physiology pre-test by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem (with outliers noted by participant number) B) Conceptual component of physiology pre-test by mathematical approach and physiology content structure for the Deep Diving challenge problem

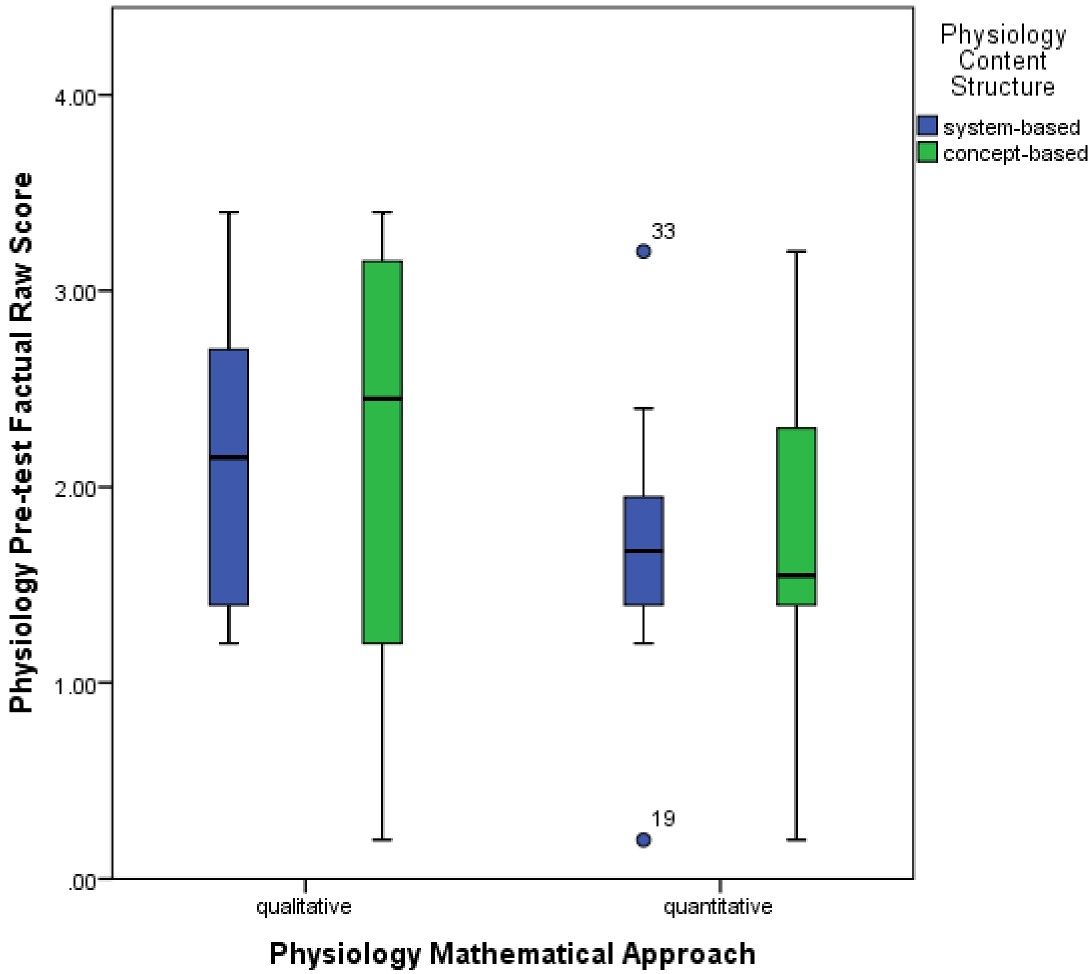


Figure 6-6**.** Conceptual component of physiology pre-test by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the conceptual pre-test component scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 0.246$, $p = 0.864$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = .010$, $p = .920$] or Mathematical Approach [$F(1,37) = 0.081$, $p = 0.778$].

6.5.1.4 Descriptive statistics and Univariate Tests of Factual Post-test component

Mean, range and standard deviation data are reported in Table 6-8. The skewness and kurtosis data are reported in Table 6-9.

TABLE 6-8. Minimum, maximum, mean, standard error of the mean and standard deviation of the conceptual component of the physiology post-test by biofluids challenge problem and physiology training experimental condition

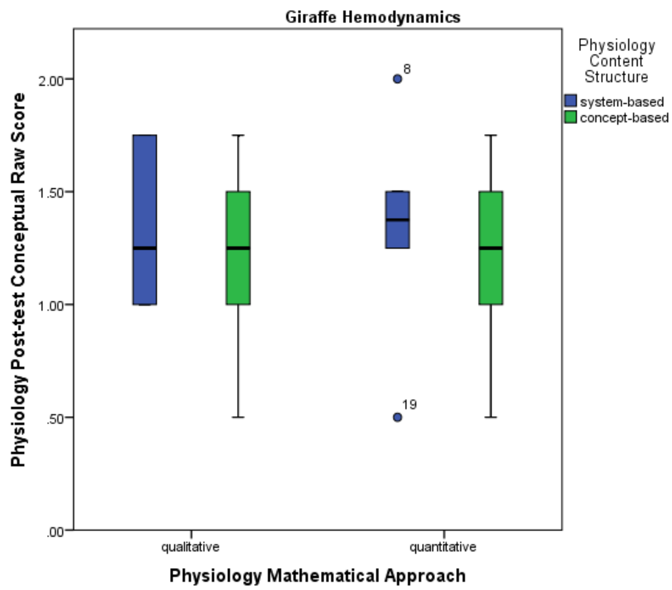
Biofluids Challenge	**Physiology Training (n)**	**Physiology Post-test Conceptual Component**				
		min	**max**	**$\bar{x}$**	**SEM**	**σ**
Giraffe	QLSB (6)	1.00	1.75	1.33	.139	.342
	QLCB (5)	.500	1.75	1.20	.215	.481
	QTSB (6)	.500	2.00	1.33	.201	.492
	QTCB (6)	.500	1.75	1.21	.176	.431
Diving	QLSB (4)	1.25	1.50	1.44	.063	.125
	QLCB (4)	.250	1.75	.938	.344	689
	QTSB (4)	1.00	1.25	1.19	.063	.125
	QTCB (6)	1.00	1.75	1.33	.124	.303

TABLE 6-9. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the conceptual component of the physiology post-test by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	.523(.845)	-.693(.845)
				Kurtosis (SE)	-1.88(1.74)	1.92(1.74)
			Concept-based	Skewness (SE)	-.590(.913)	-.678(.845)
				Kurtosis (SE)	-.022(2.00)	.814(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	-2.00(1.01)	-2.00(1.01)
				Kurtosis (SE)	4.00(2.62)	4.00(2.62)
			Concept-based	Skewness (SE)	.323(1.01)	.075(.845)
				Kurtosis (SE)	-3.03(2.62)	-1.55(1.74)

Conceptual post-test component scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-7). Since the experiment was designed to have no BCP effect, Conceptual post-test component scores were plotted by MA and CS (Figure 6-8). Outliers were noted, but not removed from the data set.

A.



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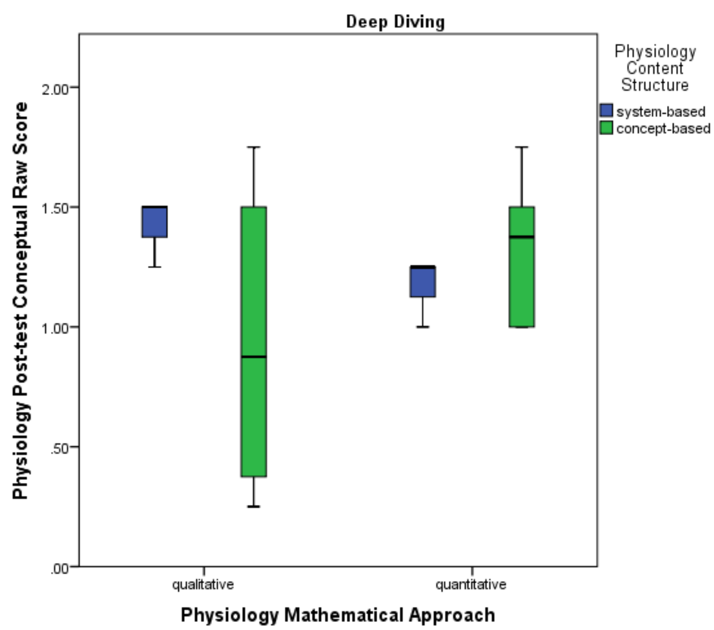


Figure 6-7. A) Conceptual component of physiology post-test by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem (with outliers noted by participant number) B) Conceptual component of physiology post-test by mathematical approach and physiology content structure for the Deep Diving challenge problem

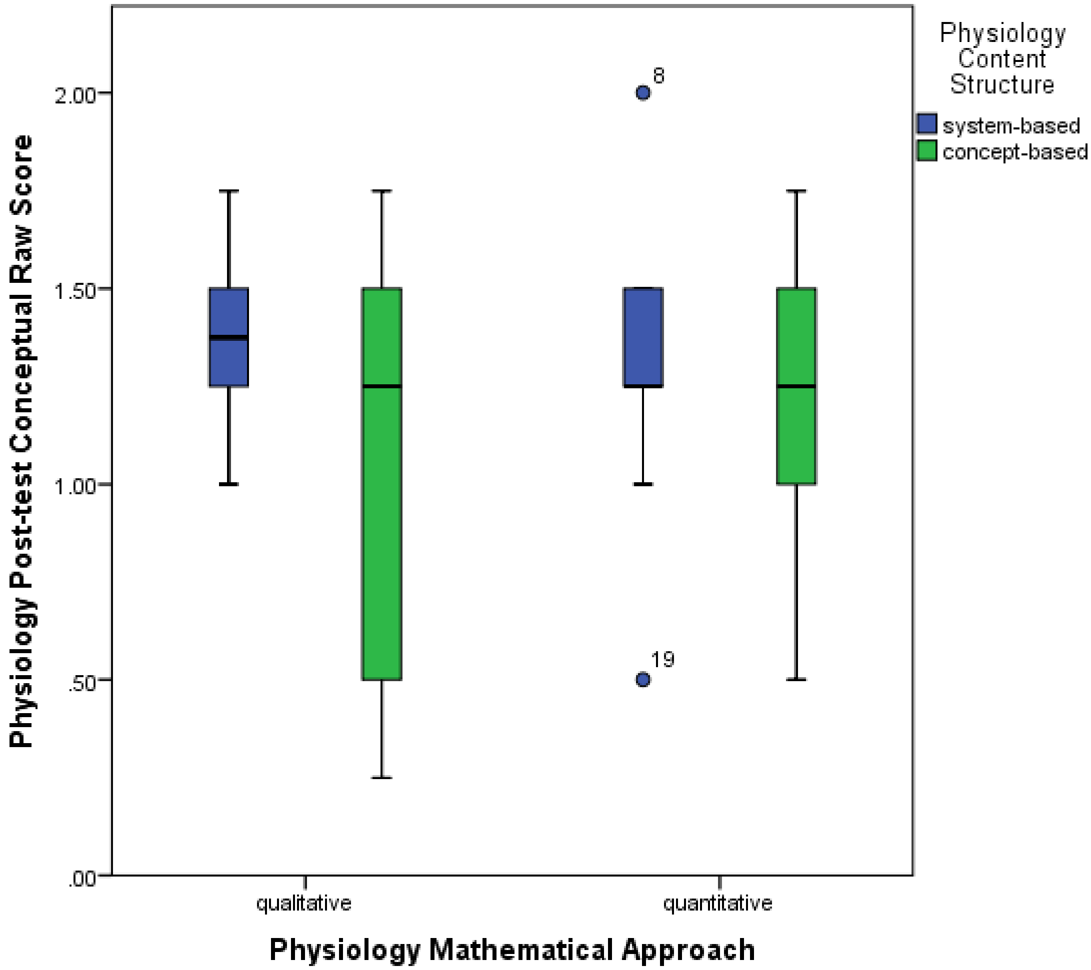


Figure 6-8. Conceptual component of physiology post-test by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the conceptual post-test component scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 2.117$, $p = 0.115$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 1.393$, $p = 0.245$] or Mathematical Approach [$F(1,37) = 0.122$, $p = 0.729$].

6.5.1.5 Descriptive statistics and Univariate Tests of Transfer component

Mean, range and standard deviation data are reported in Table 6-10. The skewness and kurtosis data are reported in Table 6-11.

TABLE 6-10. Minimum, maximum, mean, standard error of the mean and standard deviation of the physiology transfer component by biofluids challenge problem and physiology training experimental condition

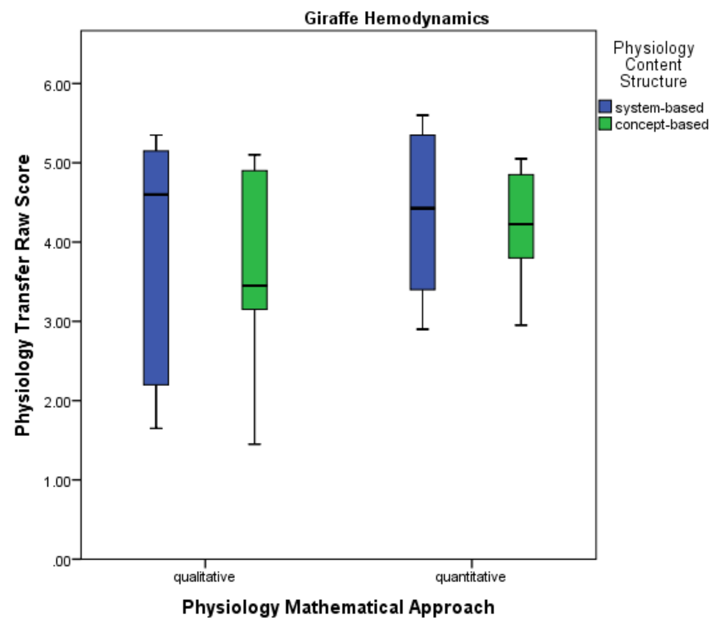
Biofluids Challenge	Physiology Training (n)	Physiology Transfer Component				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	1.65	5.35	3.93	.651	1.59
	QLCB (5)	1.45	5.10	3.61	.663	1.48
	QTSB (6)	2.90	5.60	4.35	.437	1.07
	QTCB (6)	2.95	5.05	4.18	.324	.794
Diving	QLSB (4)	2.65	4.25	3.39	.329	.658
	QLCB (4)	2.35	4.90	3.74	.665	1.33
	QTSB (4)	1.60	4.85	2.75	.721	1.44
	QTCB (6)	2.45	4.85	3.69	.423	1.04

TABLE 6-11. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the physiology transfer component by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	-.836(.845)	-.224(.845)
				Kurtosis (SE)	-1.62(1.74)	-1.62(1.72)
			Concept-based	Skewness (SE)	-.605(.913)	-.570(.845)
				Kurtosis (SE)	-.356(2.00)	-.707(1.72)
	Diving	**Content Structure**	System-based	Skewness (SE)	.562(1.01)	1.65(1.01)
				Kurtosis (SE)	1.65(2.62)	2.95(2.62)
			Concept-based	Skewness (SE)	-.120(1.01)	-.416(.845)
				Kurtosis (SE)	-5.30(2.62)	-1.92(1.74)

Physiology transfer component scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-9). Since the experiment was designed to have no BCP effect, Transfer component scores were plotted by MA and CS (Figure 6-10). Outliers were noted, but not removed from the data set.

A.



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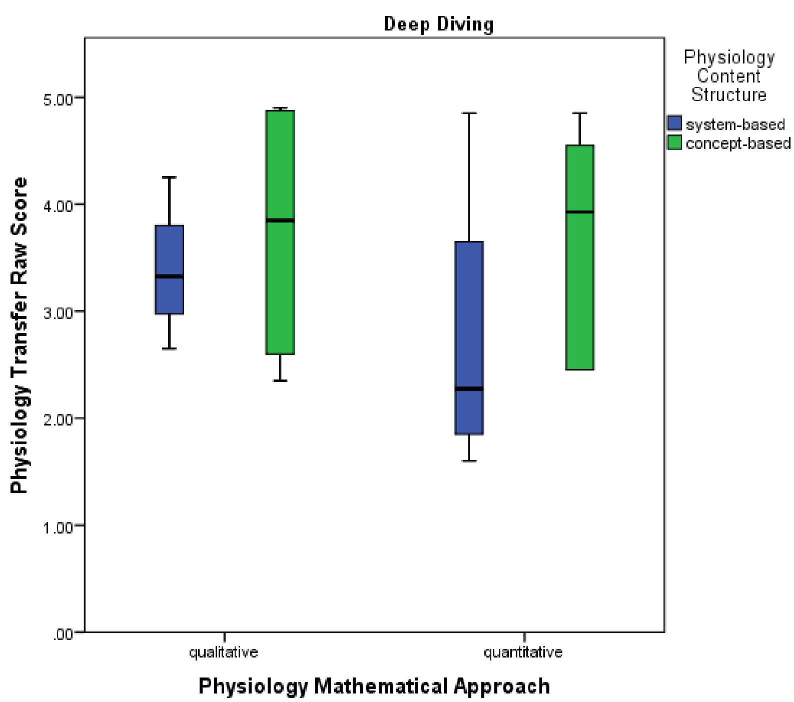


Figure 6-9. A) Physiology transfer component by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem B) Physiology transfer component by mathematical approach and physiology content structure for the Deep Diving challenge problem

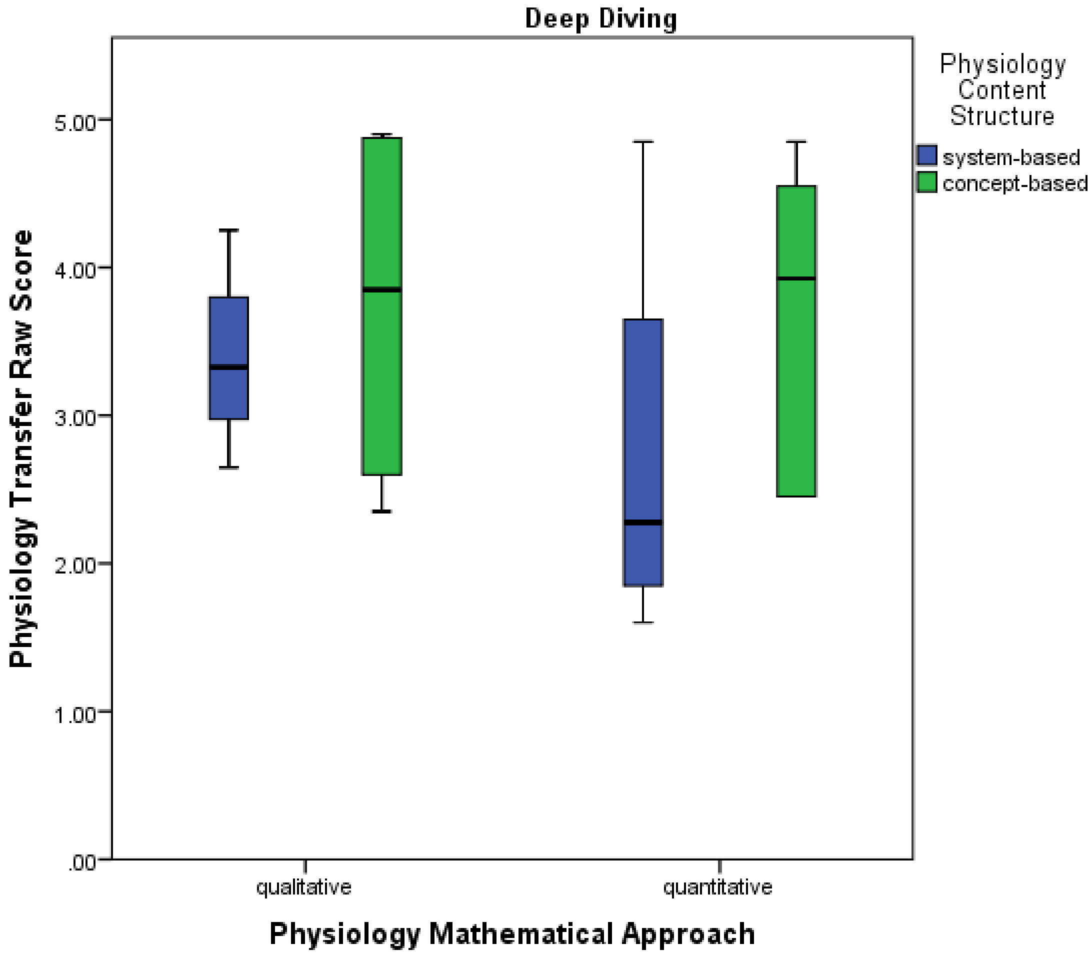


Figure 6-10. Physiology transfer component by mathematical approach and physiology content structure

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the physiology transfer component scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 1.590$, $p = 0.208$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.057$, $p = .813$] or Mathematical Approach [$F(1,37) = 0.122$, $p = 0.728$].

6.5.2 Analyses of Physiology Learning Gains

Two learning gains were calculated using the physiology scores: 1) Physiology pre/post and Physiology post/transfer. These learning gains are analyzed below.

6.5.2.1 Descriptive statistics and Univariate Tests of Pre/Post Learning Gain

Mean, range and standard deviation data are reported in Table 6-12. The skewness and kurtosis data are reported in Table 6-13.

TABLE 6-12. Minimum, maximum, mean, standard error of the mean and standard deviation of the physiology pre/post learning gain by biofluids challenge problem and physiology training experimental condition

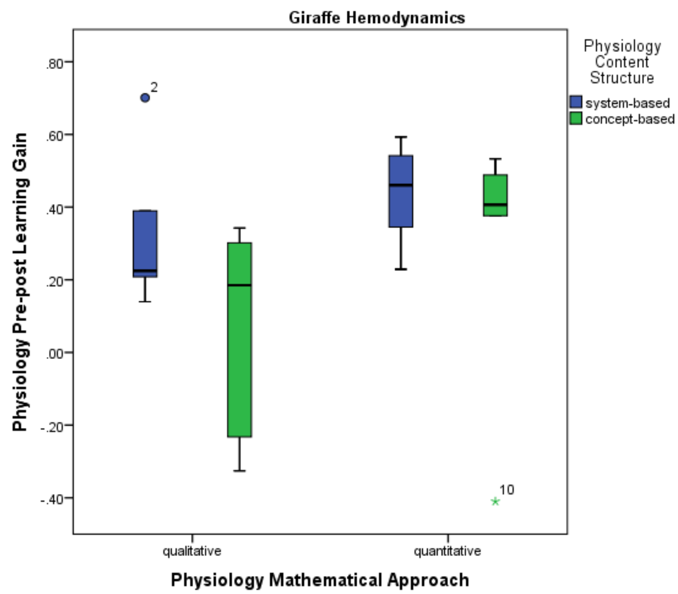
Biofluids Challenge	**Physiology Training (n)**		**Physiology Pre/Post Learning Gain**			
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	.140	.700	.315	.084	.207
	QLCB (5)	-.330	.340	.054	.139	.312
	QTSB (6)	.230	.590	.438	.054	.133
	QTCB (6)	-.410	.530	.300	.144	.353
Diving	QLSB (4)	.060	.550	.289	.101	.202
	QLCB (4)	-.520	.550	.121	.240	.480
	QTSB (4)	-.390	.490	.115	.189	.378
	QTCB (6)	.020	.830	.291	.117	.286

TABLE 6-13. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the physiology pre/post learning gain by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	1.70(.845)	-.656(.845)
				Kurtosis (SE)	2.79(1.74)	-.215(1.74)
			Concept-based	Skewness (SE)	-.512(.913)	-2.29(.845)
				Kurtosis (SE)	-2.88(2.00)	5.43(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	.388(1.01)	-.929(1.01)
				Kurtosis (SE)	1.48(2.62)	.834(2.62)
			Concept-based	Skewness (SE)	-.975(1.01)	1.63(.845)
				Kurtosis (SE)	-.111(2.62)	3.07(1.74)

Pre/post learning gain scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-11). Since the experiment was designed to have no BCP effect, Transfer component scores were plotted by MA and CS (Figure 6-12). Outliers were noted, but not removed from the data set.

A.



B.

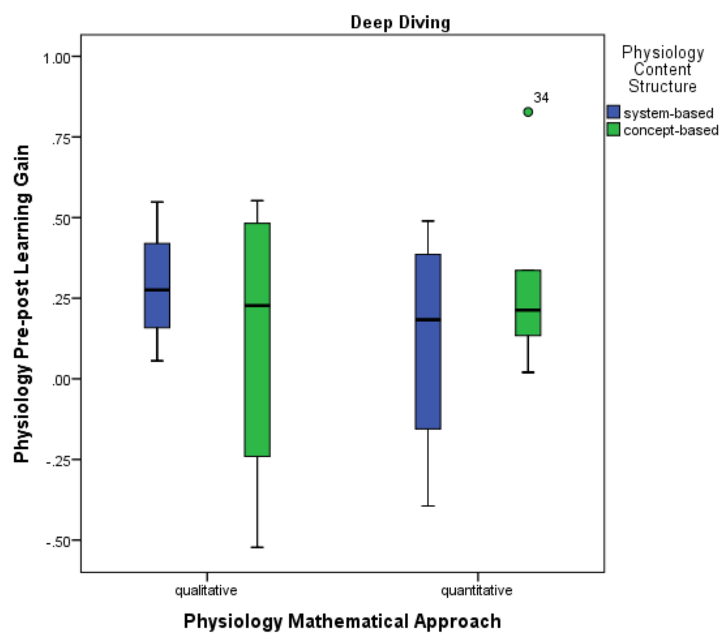


Figure 6-11. A) Physiology pre/post learning gain by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem (with outliers noted by participant number)   B) Physiology pre/post learning gain by mathematical approach and physiology content structure for the Deep Diving challenge problem (with outliers noted by participant number

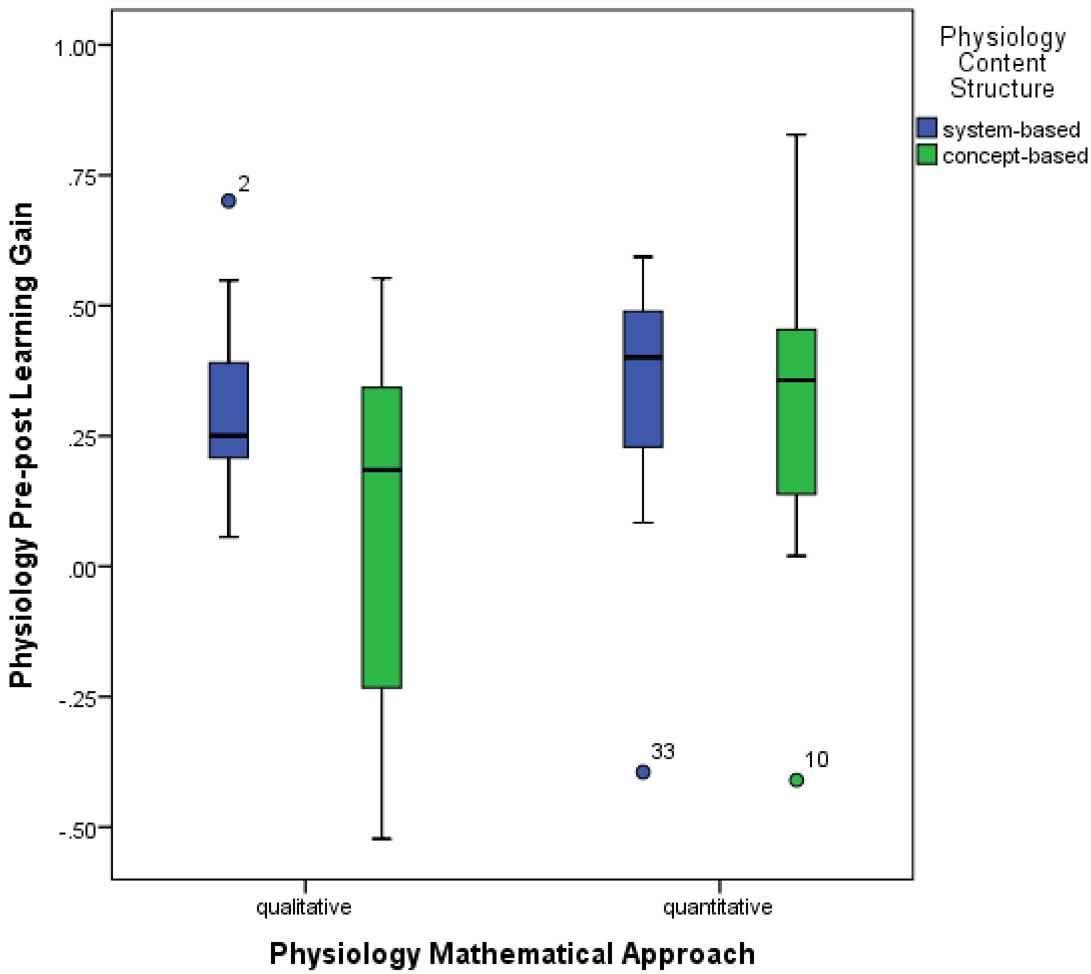


Figure 6-12**.** Physiology pre/post learning gain by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the pre/post learning gain scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 1.290$, $p = 0.292$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 1.595$, $p = .215$] or Mathematical Approach [$F(1,37) = 1.358$, $p = 0.251$].

6.5.2.2 Descriptive statistics and Univariate Tests of Post/Transfer Learning Gain

Mean, range and standard deviation data are reported in Table 6-14. The skewness and kurtosis data are reported in Table 6-15.

TABLE 6-14. Minimum, maximum, mean, standard error of the mean and standard deviation of the physiology post/transfer learning gain by biofluids challenge problem and physiology training experimental condition

Biofluids Challenge	Physiology Training (n)	Physiology Post/Transfer Learning Gain				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	-1.04	.460	-.172	.282	.690
	QLCB (5)	-.170	.480	.140	.117	.262
	QTSB (6)	-.860	.570	-.014	.241	.591
	QTCB (6)	-.280	.430	.146	.108	.265
Diving	QLSB (4)	-1.61	.140	-.405	.410	.820
	QLCB (4)	-1.74	.590	-.212	.526	1.05
	QTSB (4)	-.480	.090	-.154	.129	.258
	QTCB (6)	-2.27	.260	-.378	.387	.947

TABLE 6-15. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the physiology post/transfer learning gain by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	-.270(.845)	-.765(.845)
				Kurtosis (SE)	-.262(1.74)	-1.52(1.74)
			Concept-based	Skewness (SE)	.201(.913)	-.551(.845)
				Kurtosis (SE)	-1.55(2.00)	.156(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	-1.75(1.01)	-.718(1.01)
				Kurtosis (SE)	3.00(2.62)	-1.39(2.62)
			Concept-based	Skewness (SE)	-1.61(1.01)	-2.21(.845)
				Kurtosis (SE)	2.55(2.62)	5.06(1.72)

Post/transfer learning gain scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-13). Since the experiment was designed to have no BCP effect, Post/transfer learning gain scores were plotted by MA and CS (Figure 6-14). Outliers were noted, but not removed from the data set.

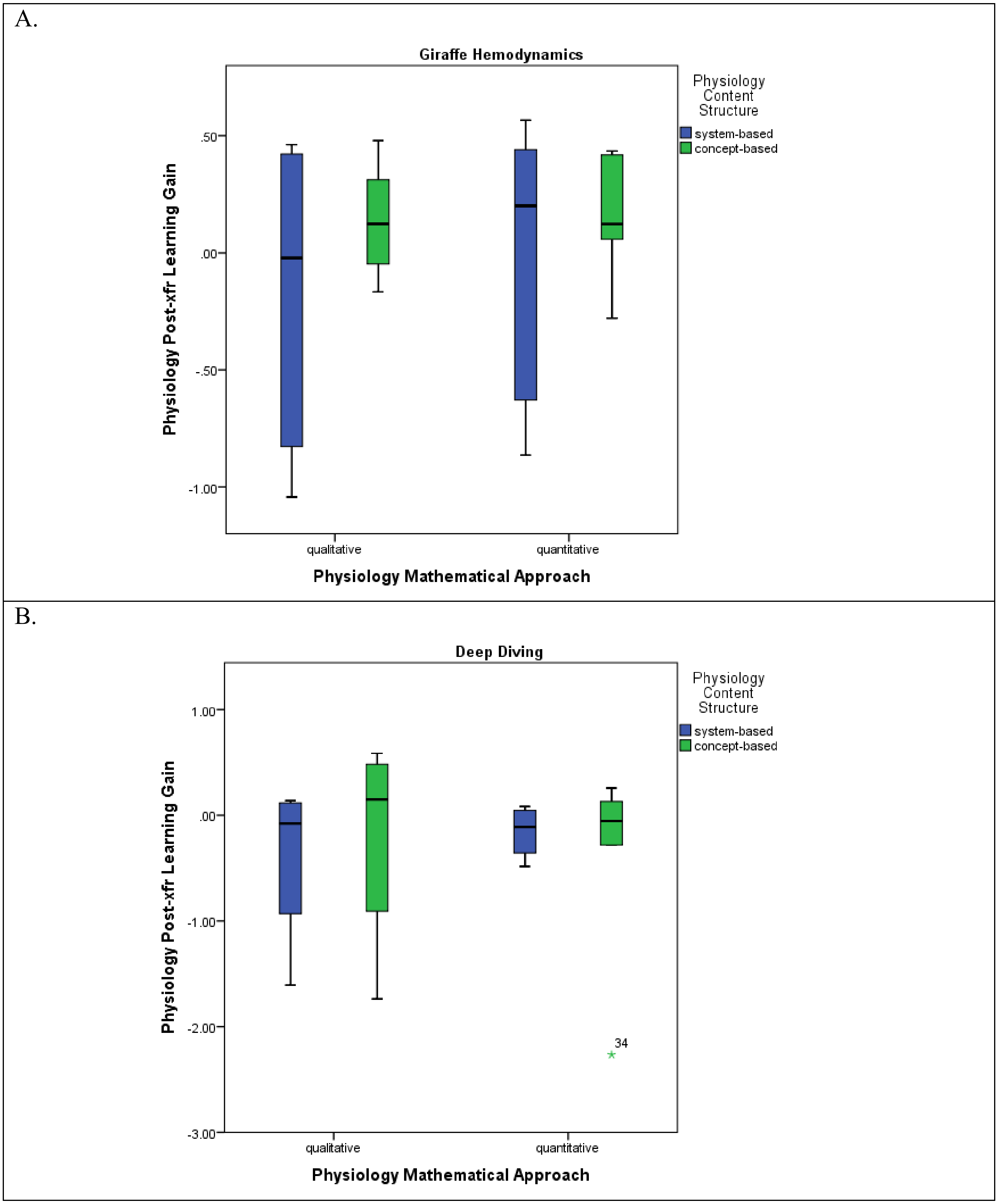


Figure 6-13. A) Physiology post/transfer learning gain by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem B) Physiology post/transfer learning gain by mathematical approach and physiology content structure for the Deep Diving challenge problem (34 is an extreme outlier)

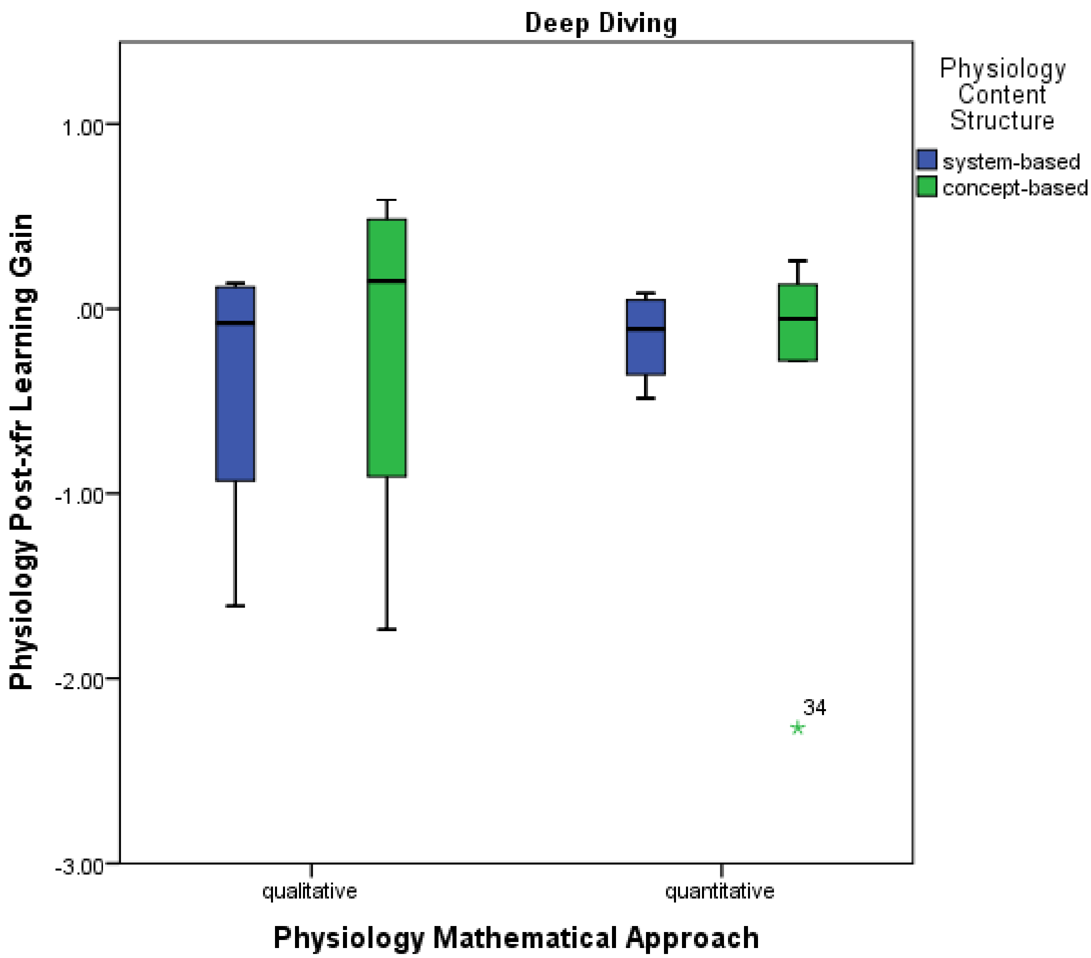


Figure 6-14**.** Physiology post/transfer learning gain by mathematical approach and physiology content structure (34 is an extreme outlier)

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the post/transfer learning gain scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 0.352$, $p = 0.788$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.241$, $p = 0.627$] or Mathematical Approach [$F(1,37) = 0.054$, $p = 0.818$].

6.5.2.3 Descriptive statistics and Univariate Tests of Factual Pre/Post Learning Gain

Mean, range and standard deviation data are reported in Table 6-16. The skewness and kurtosis data are reported in Table 6-17.

TABLE 6-16. Minimum, maximum, mean, standard error of the mean and standard deviation of the physiology factual pre/post learning gain by biofluids challenge problem and physiology training experimental condition

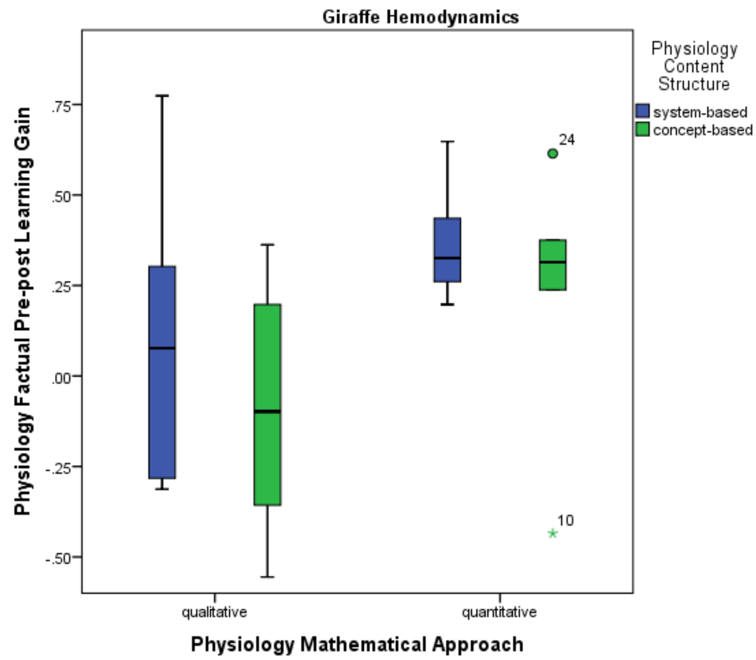
Biofluids Challenge	Physiology Training (n)	Physiology Factual Pre/Post Learning Gain				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	-.310	.770	.106	.165	.404
	QLCB (5)	-.560	.360	-.090	.170	.379
	QTSB (6)	.200	.650	.366	.066	.162
	QTCB (6)	-.430	.610	.237	.145	.355
Diving	QLSB (4)	-.190	.510	.180	.157	.314
	QLCB (4)	-1.09	.510	-.168	.375	.751
	QTSB (4)	-1.14	.630	-.150	.366	.732
	QTCB (6)	-.300	.930	.157	.172	.421

TABLE 6-17. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the physiology factual pre/post learning gain by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	.793(.845)	1.15(.845)
				Kurtosis (SE)	.456(1.74)	1.19(1.74)
			Concept-based	Skewness (SE)	-.025(.913)	-1.64(.845)
				Kurtosis (SE)	-1.91(2.00)	3.65(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	-.268(1.01)	-.841(1.01)
				Kurtosis (SE)	-2.14(2.62)	1.77(2.62)
			Concept-based	Skewness (SE)	-.550(1.01)	1.41(.845)
				Kurtosis (SE)	-2.63(2.62)	2.53(1.74)

Factual pre/post gain scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-15). Since the experiment was designed to have no BCP effect, factual pre/post learning gain scores were plotted by MA and CS (Figure 6-16). Outliers were noted, but not removed from the data set.

A.



B.

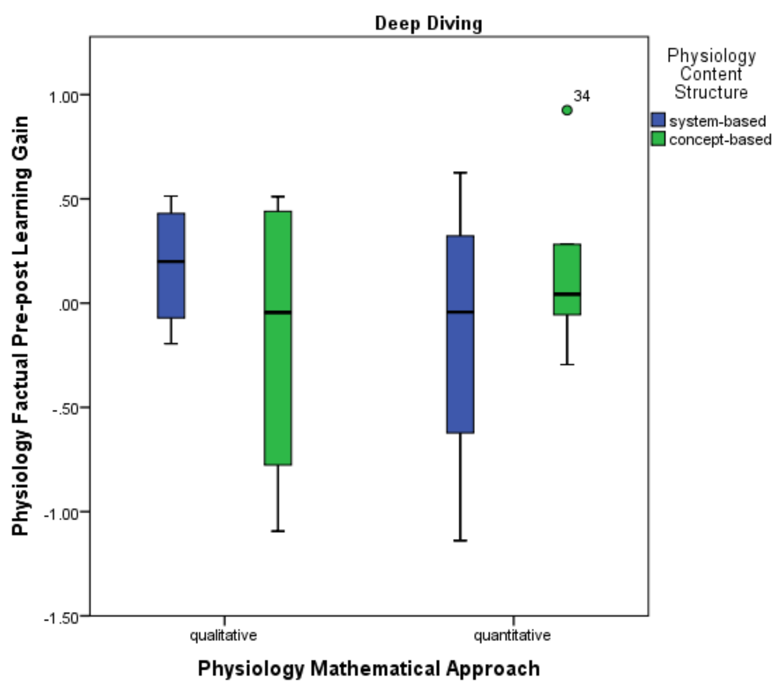


Figure 6-15. A) Physiology factual pre/post learning gain by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem with outliers noted by participant number (10 is an extreme outlier) B) Physiology factual pre/post learning gain by mathematical approach and physiology content structure for the Deep Diving challenge problem with outliers noted by participant number

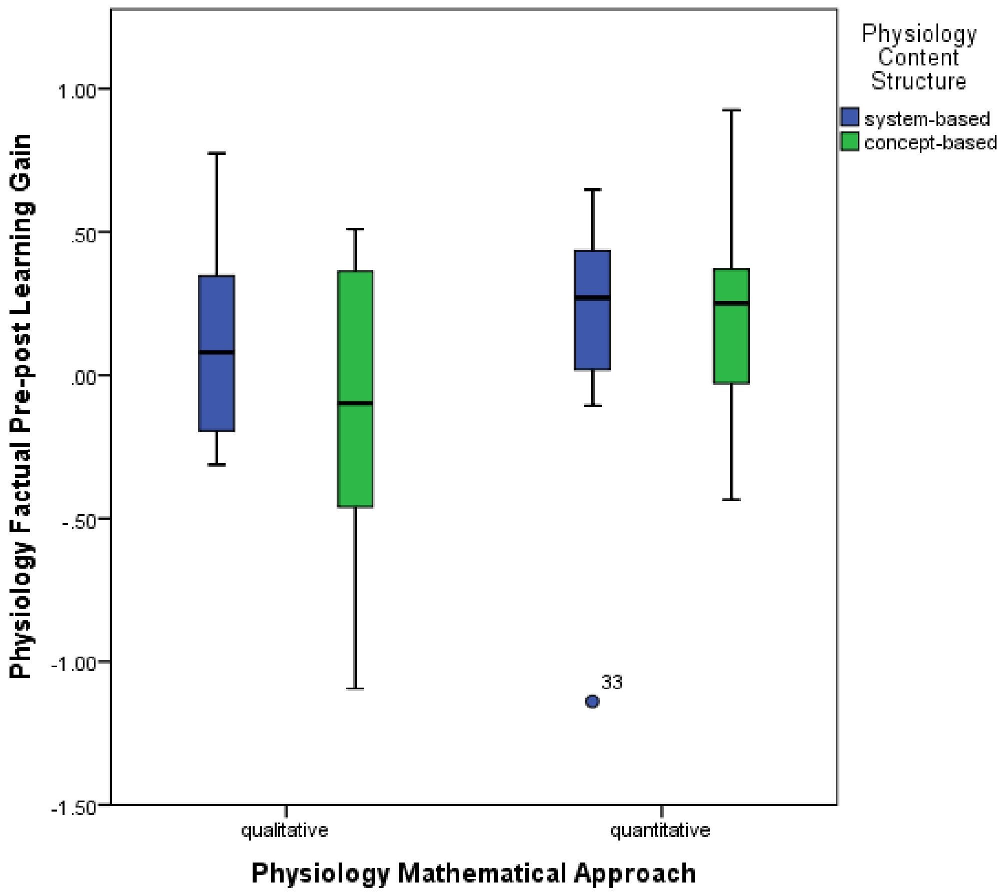


Figure 6-16. Physiology factual pre/post learning gain by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the factual pre/post learning gain scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 0.724$, $p = 0.544$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.635$, $p = .431$] or Mathematical Approach [$F(1,37) = 1.532$, $p = 0.224$].

6.5.2.4 Descriptive statistics and Univariate Tests of Conceptual Pre/Post Gain

Mean, range and standard deviation data are reported in Table 6-18. The skewness and kurtosis data are reported in Table 6-19.

TABLE 6-18. Minimum, maximum, mean, standard error of the mean and standard deviation of the physiology conceptual pre/post learning gain by biofluids challenge problem and physiology training experimental condition

Biofluids Challenge	Physiology Training (n)		Physiology Conceptual Pre/Post Learning Gain			
		min	max	$\bar{x}$	SEM	σ
Giraffe	QLSB (6)	.000	.860	.537	.133	.325
	QLCB (5)	.000	.670	.383	.117	.261
	QTSB (6)	.140	1.00	.545	.121	.296
	QTCB (6)	-.330	.860	.422	.179	.439
Diving	QLSB (4)	.000	.710	.471	.160	.320
	QLCB (4)	.000	.830	.387	.192	.384
	QTSB (4)	.000	.630	.406	.139	.277
	QTCB (6)	.250	.860	.506	.806	.198

TABLE 6-19. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for the physiology conceptual pre/post learning gain by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	-.900(.845)	.260(.845)
				Kurtosis (SE)	.191(1.74)	.292(1.74)
			Concept-based	Skewness (SE)	-.769(.913)	-1.22(.845)
				Kurtosis (SE)	-.248(2.00)	.809(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	-1.77(1.01)	-1.72(1.01)
				Kurtosis (SE)	3.37(2.62)	3.27(2.62)
			Concept-based	Skewness (SE)	.268(1.01)	1.02(.845)
				Kurtosis (SE)	-3.27(2.62)	2.75(1.74)

Conceptual pre/post learning gain scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-17). Since the experiment was designed to have no BCP effect, conceptual pre/post learning gain scores were plotted by MA and CS (Figure 6-18). Outliers were noted, but not removed from the data set.

A.

B.

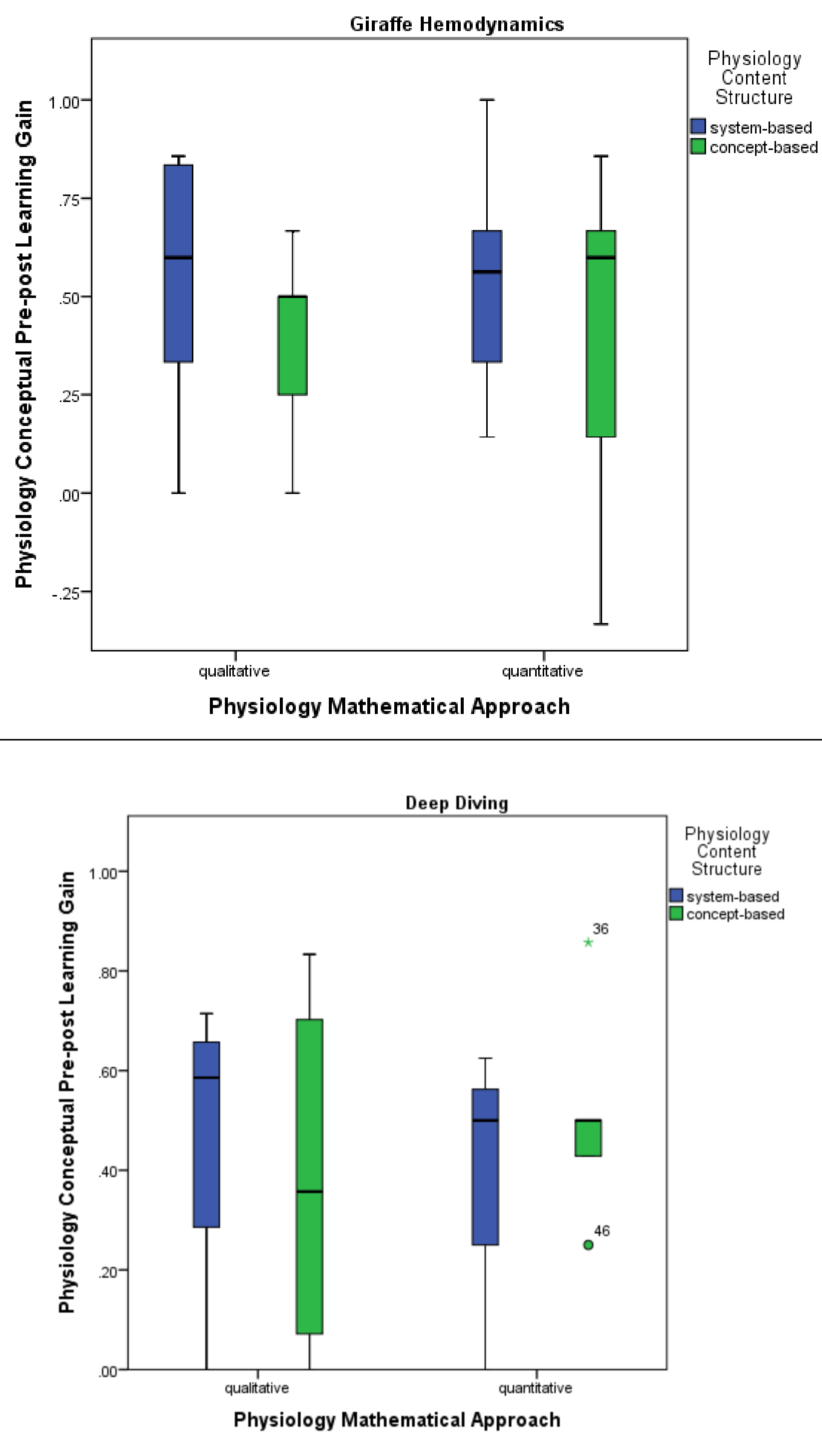


Figure 6-17. A) Physiology conceptual pre/post learning gain by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem B) Physiology conceptual pre/post learning gain by mathematical approach and physiology content structure for the Deep Diving challenge problem with outliers noted by participant number (36 is an extreme outlier)

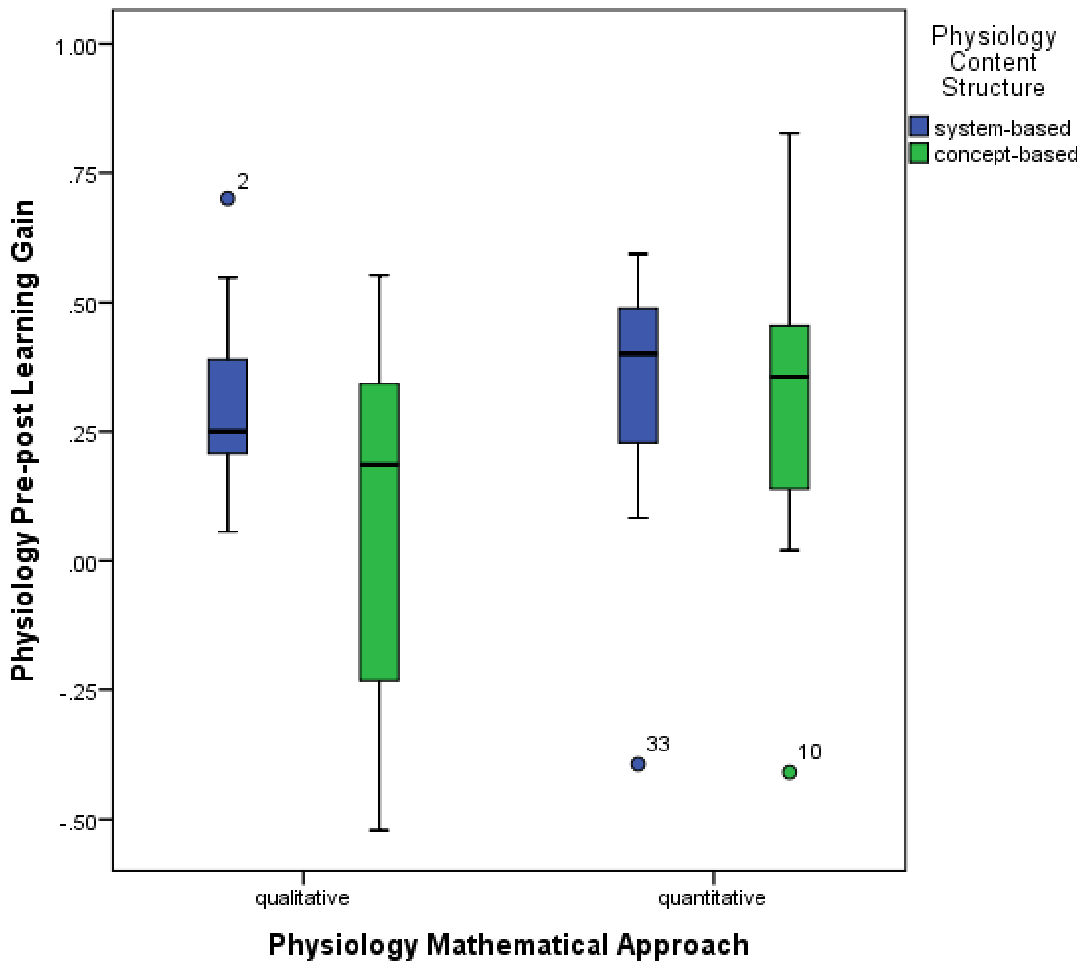


Figure 6-18. Physiology conceptual pre/post learning gain by mathematical approach and physiology content structure with outliers noted by participant number

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the conceptual pre/post learning gain scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 0.160$, $p = 0.92e$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.621$, $p = 0.436$] or Mathematical Approach [$F(1,37) = 0.090$, $p = 0.766$].

6.5.3 Analysis of Adaptive Expertise in Physiology (AEP)

Adaptive expertise in physiology (AEP) was calculated using the physiology factual pre/post learning gain, conceptual pre/post learning gain and post/transfer learning gain.

6.5.3.1 Descriptive statistics and univariate analysis of AEP

Mean, range and standard deviation data are reported in Table 6-20. The skewness and kurtosis data are reported in Table 6-21.

TABLE 6-20. Minimum, maximum, mean, standard error of the mean and standard deviation of the adaptive expertise in physiology gain by biofluids challenge problem and physiology training experimental condition

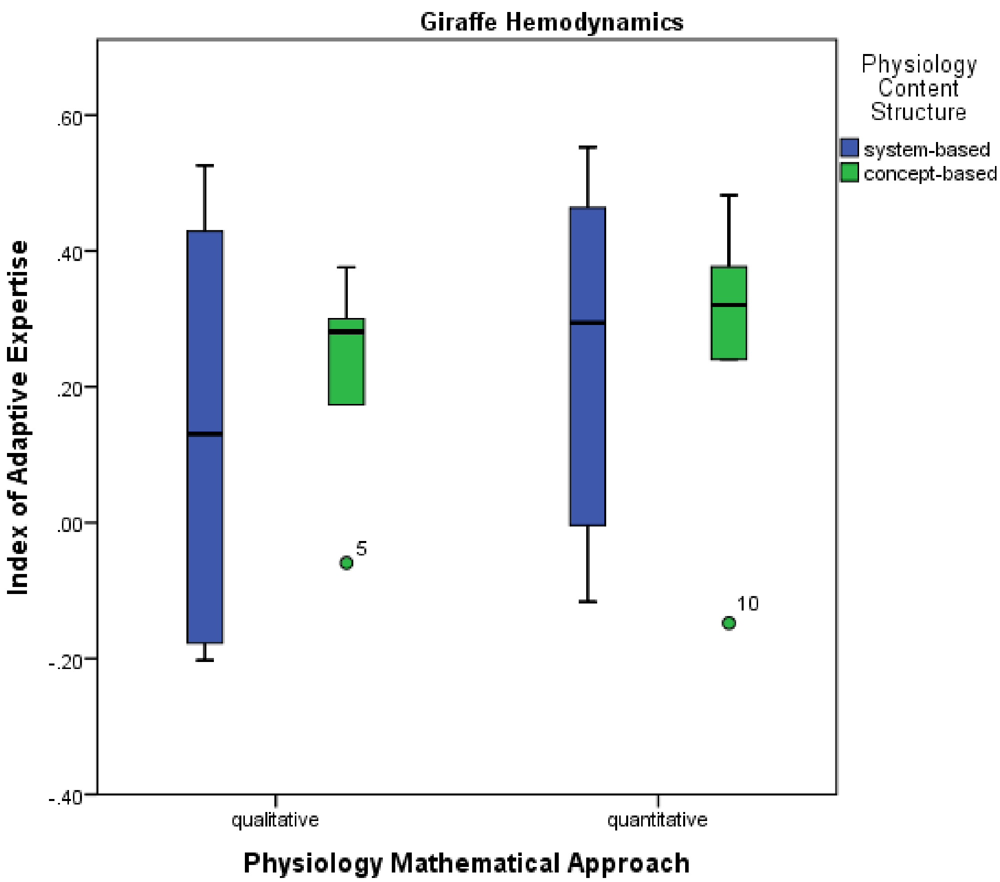
Biofluids Challenge	Physiology Training (n)	Adaptive Expertise in Physiology				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	-.200	.530	.139	.137	.336
	QLCB (5)	-.060	.380	.214	.076	.169
	QTSB (6)	-.120	.550	.247	.108	.264
	QTCB (6)	-.150	.480	.265	.089	.218
Diving	QLSB (4)	-.510	.340	.004	.197	.393
	QLCB (4)	-.500	.370	.032	.187	.374
	QTSB (4)	.010	.110	.071	.021	.042
	QTCB (6)	-.840	.410	.029	.181	.444

TABLE 6-21. Skewness (SE Skewness) and kurtosis (SE Kurtosis) statistics for adaptive expertise in physiology by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	**Content Structure**	System-based	Skewness (SE)	.057(.845)	-.390(.845)
				Kurtosis (SE)	-2.98(1.74)	-1.57(1.74)
			Concept-based	Skewness (SE)	-1.33(.913)	-1.71(.845)
				Kurtosis (SE)	1.71(2.00)	3.58(1.74)
	Diving	**Content Structure**	System-based	Skewness (SE)	-.876(1.01)	-1.54(1.01)
				Kurtosis (SE)	-1.01(2.62)	2.47(2.62)
			Concept-based	Skewness (SE)	-1.35(1.01)	-2.03(.845)
				Kurtosis (SE)	2.20(2.62)	4.55(1.74)

Adaptive expertise in physiology scores were plotted by physiology experimental condition for both the Giraffe Hemodynamics and Deep Diving biofluids challenge problems (Figure 6-19). Since the experiment was designed to have no BCP effect, adaptive expertise scores were plotted by MA and CS (Figure 6-20). Outliers were noted, but not removed from the data set.

A.



B.

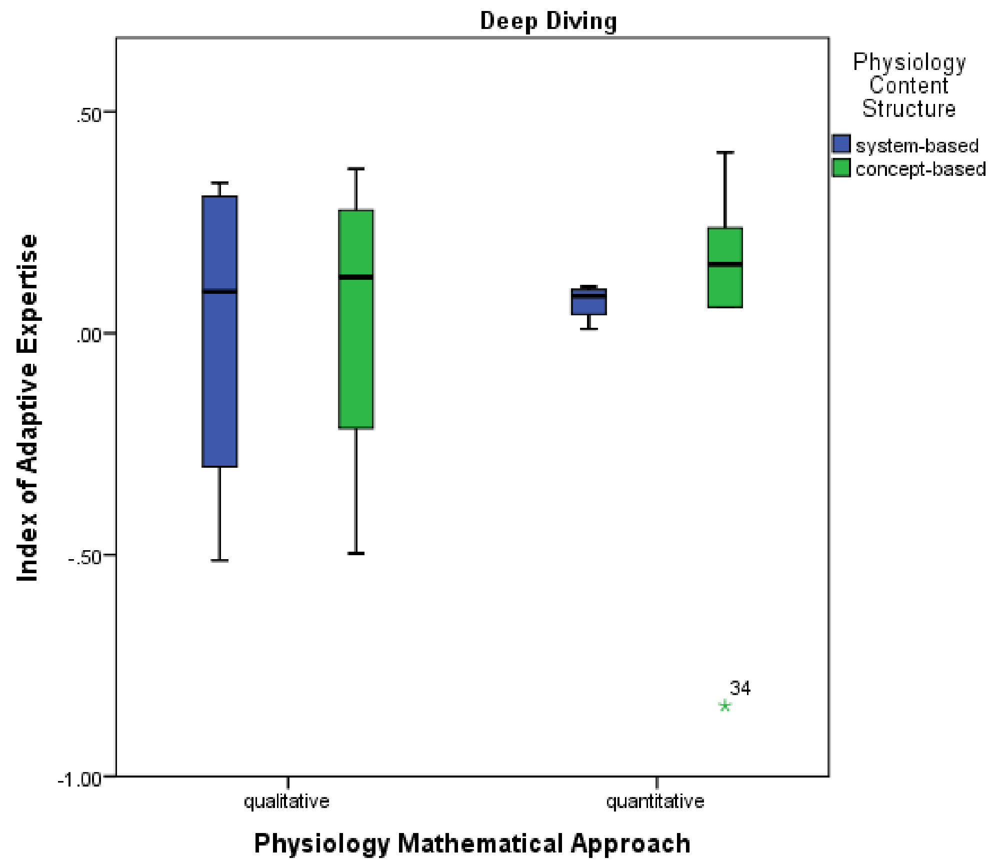


Figure 6-19. A) Adaptive expertise in physiology by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem with outliers noted by participant number B) Adaptive expertise in physiology by mathematical approach and physiology content structure for the Deep Diving challenge problem (34 is an extreme outlier)

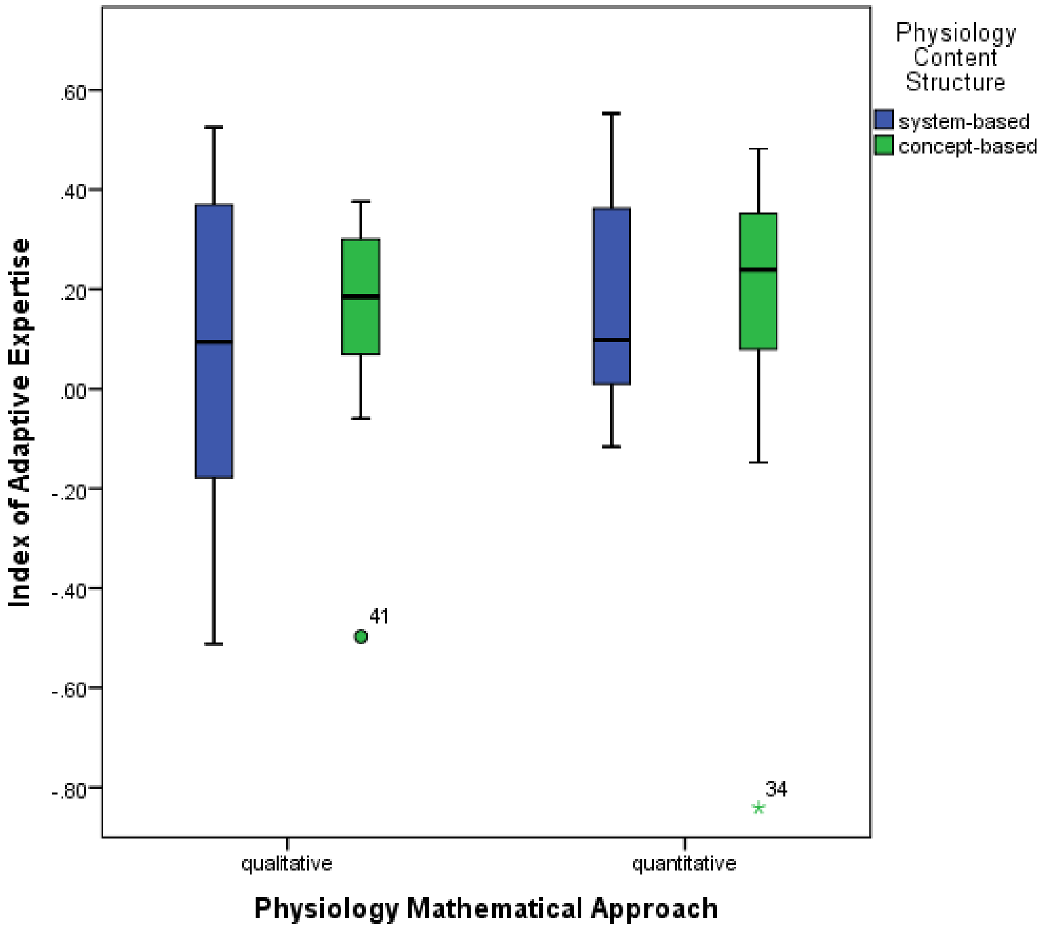


Figure 6-20. Adaptive expertise in physiology (AEP) by mathematical approach and physiology content structure with outliers noted by participant number (34 is an extreme outlier)

A two-way analysis of variance (ANOVA) model was used to explore mean differences in the AEP scores for Mathematical Approach and Content Structure. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 0.892$, $p = 0.454$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = 0.009$, $p = 0.923$] or Mathematical Approach [$F(1,37) = 0.299$, $p = 0.588$].

6.5.3.2 Effect size and power analysis of AEP

The data means and pooled standard deviation (σ_{pooled}) were used to find Cohen's *d* (Equation 6-5) as a measure of effect size for two independent groups (Cohen, 1988). A post hoc power analysis was completed. Effect size *d* was used along with the α-error probability for a two-tail test (0.05) and the experimental group sample sizes. Power was determined with statistical software G*Power version 3.1.5 (Faul, Erdfelder, Lang, & Buchner, 2007). The effect sizes and post hoc power analysis results are reported in Table 6-22.

$$d = \frac{\bar{x}_1 - \bar{x}_2}{\sigma_{pooled}} \quad , \quad \text{where} \quad \sigma_{pooled} = \sqrt{\frac{\sigma_1^2(n_1 - 1) + \sigma_2^2(n_2 - 1)}{n_1 + n_2 - 2}} \qquad \textbf{Equation 6-5}$$

Since effect size is the strength of the effect that the independent variable has on the dependent variable, to interpret the effect sizes, the percent of non-overlap of the scores for distributions of each group was noted. The percentage of non-overlap for the independent groups was interpolated for each dependent variable using tables for the interpolation of Cohen's *d* (Cohen, 1988). The percentage of non-overlap for the two content structure distributions was 1.20% (effect size = 0.033). Finally, the percentage of non-overlap for the two mathematical approach distributions was 7.97% (effect size = 0.18).

With the small effect sizes and small sample sizes, the power for all of the dependent variable group comparisons was low. Using the calculated effect sizes, an a priori power analysis was completed to determine what sample size would give a power of 0.80. To test of AEP with the only the content structure variable would require 35,074 participants and to test mathematical approach, 978 participants would be needed.

TABLE 6-22. Means, effect sizes and post hoc power results of distributions of AEP scores for mathematical approach (MA) and content structure (CS)

Variable	Grp 1 (n_1)	Grp 2 (n_2)	$\bar{x}_1$	$\bar{x}_2$	σ_1	σ_2	d	Power
CS	SB (20)	CB (21)	0.131	0.141	0.285	0.316	-0.03	0.051
MA	QL (19)	QT (22)	0.108	0.161	0.307	0.295	-0.18	0.087

6.5.4 Analysis of Biofluids Learning Gain scores

6.5.4.1 Descriptive statistics and univariate analysis of BLG

For the biofluids learning gain scores, the descriptive statistics are reported in Table 6-23. To determine the appropriate statistical test to evaluate the main and interaction effects, skewness and kurtosis and their standard errors were calculated (Table 6-24).

TABLE 6-23. Minimum, maximum, mean, standard error of the mean and standard deviation of BLG scores by biofluids challenge problem and physiology training experimental condition

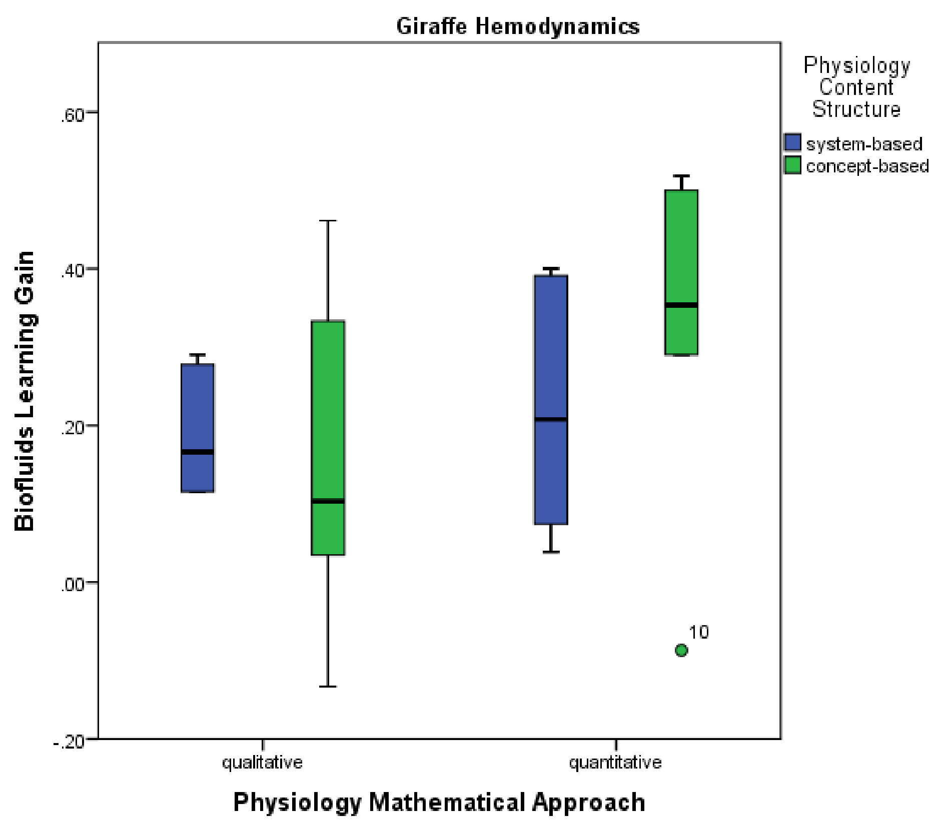
Biofluids Challenge	Physiology Training (n)	Biofluids Learning Gain (BLG)				
		min	**max**	$\bar{x}$	**SEM**	σ
Giraffe	QLSB (6)	.120	.290	.189	.032	.078
	QLCB (5)	-.130	.460	.160	.106	.238
	QTSB (6)	.040	.400	.220	.066	.161
	QTCB (6)	-.090	.520	.322	.090	.219
Diving	QLSB (4)	.040	.500	.326	.103	.205
	QLCB (4)	-.250	.440	.136	.144	.288
	QTSB (4)	-.270	.500	.043	.164	.329
	QTCB (6)	-.100	.270	.176	.058	.142

TABLE 6-24. Skewness (SE Skewness) and Kurtosis (SE Kurtosis) statistics for BLG by biofluids challenge problem and physiology training experimental condition

					Mathematical Approach	
					Qualitative	Quantitative
Biofluids Challenge	Giraffe	Content Structure	System-based	Skewness (SE)	.567 (.845)	.094 (.845)
				Kurtosis (SE)	-1.98 (1.74)	-2.57 (1.74)
			Concept-based	Skewness (SE)	.164(.913)	-1.56 (.845)
				Kurtosis (SE)	-1.41(2.00)	2.93(1.74)
	Diving	Content Structure	System-based	Skewness (SE)	-1.38 (1.01)	1.19 (1.01)
				Kurtosis (SE)	1.82 (2.62)	1.71 (2.62)
			Concept-based	Skewness (SE)	-.786(1.01)	-2.08 (.845)
				Kurtosis (SE)	1.46 (2.62)	4.53 (1.74)

Biofluid learning gain scores were compared by physiology experimental condition for each of the biofluids challenge problems (Figure 6-21) and also plotted for mathematical approach and content structure only (Figure 6-22).

A.



B.

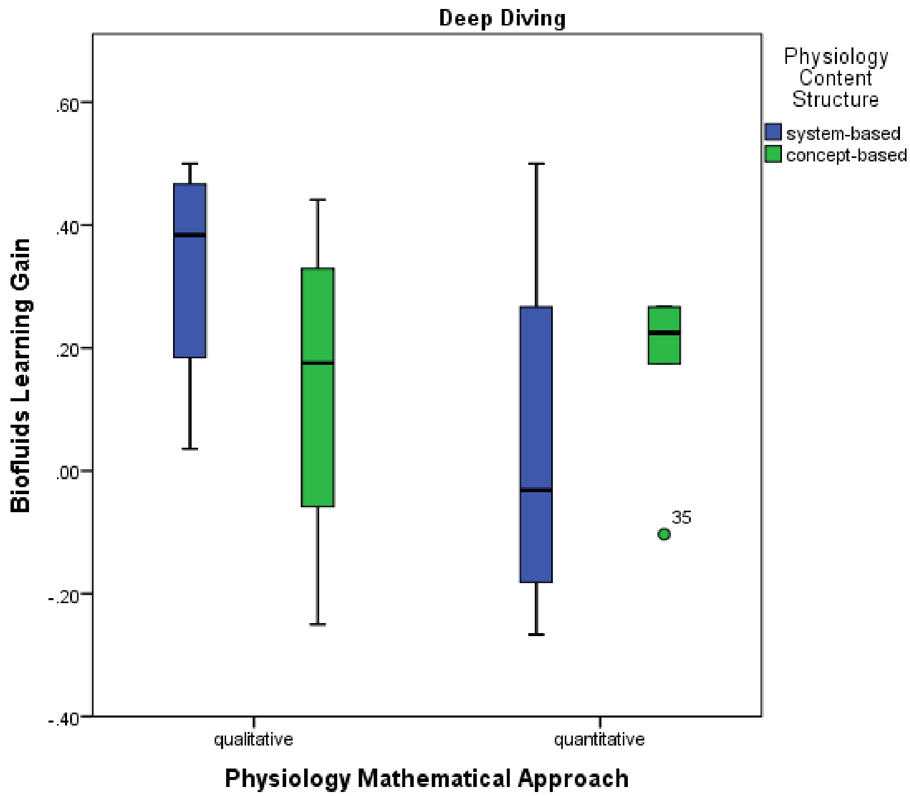


Figure 6-21. A) Biofluids Learning Gain by mathematical approach and physiology content structure for the Giraffe Hemodynamics challenge problem with outliers noted. B) Biofluids Learning Gain by mathematical approach and physiology content structure for the Deep Diving challenge problem with outliers noted.

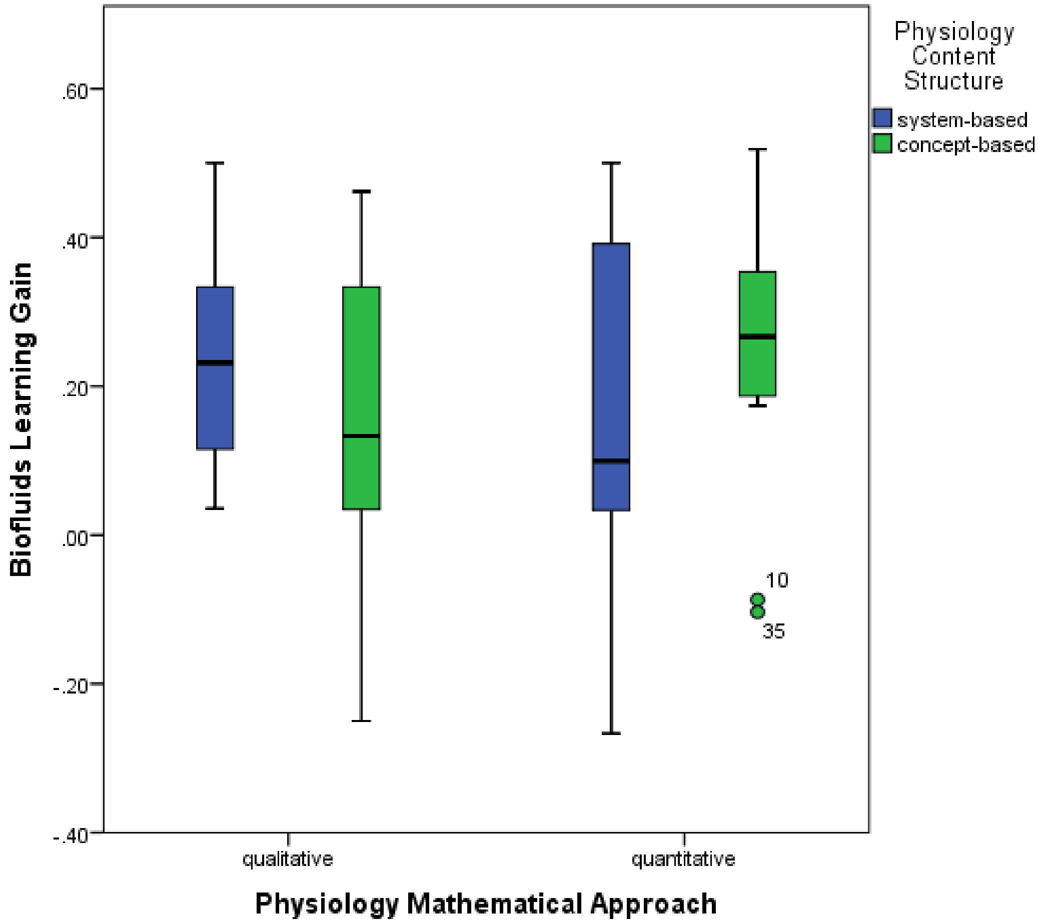


Figure 6-22**.** Biofluids learning gain by mathematical approach and physiology content structure with outliers noted

An analysis of variance (ANOVA) model was used to explore mean differences in BLG scores. The assumptions required for the ANOVA were met including the assumption that the variances were homogenous. Levene's test of homogeneity was not significant [$F(3,37) = 1.006$, $p = 0.401$]. The two-way analysis of variance results yielded no significant effects for Physiology Content Structure [$F(1,37) = .002$, $p = .968$] or Mathematical Approach [$F(1,37) = .002$, $p = .969$]

6.5.4.2 Effect size and power analysis

Effect sizes were calculated using data means and pooled standard deviation. A post hoc power analysis was completed using the effect size *d*, the α-error probability for a two-tail test (0.05) and the experimental group sample sizes. The effect sizes and post hoc power analysis results for Biofluid Learning Gain are reported in Table 6-25. The percentage of non-overlap for the two content structure distributions was 2.0% (effect size = 0.05). The percentage of non-overlap for the two mathematical approach distributions was 0.798% (effect size = 0.02).

As with AEP, the power for all of the dependent variable group comparisons on the Biofluids Learning Gain variable was low. An a priori power analysis showed that to test only content structure variable would require 12,628 participants and to test mathematical approach 16,148 participants would be needed.

TABLE 6-25. Means, effect sizes and post hoc power results of distributions of Biofluid Learning Gain scores for mathematical approach (MA) and content structure (CS)

Variable	Grp 1 (n_1)	Grp 2 (n_2)	$\bar{x}_1$	$\bar{x}_2$	σ_1	σ_2	d	Power
CS	SB (20)	CB (21)	.196	.206	.202	.216	-0.05	.053
MA	QL (19)	QT (22)	.199	.203	.200	.217	-0.02	.022

6.6 Validity and Reliability

The physiology pre/post and transfer assessments, as well as the biofluids assessments, were presented using the online quiz tool in the Moodle™ course management system. All participants completed the same physiology pre/post and transfer assessments as well as the same biofluids pre/post assessment. Overall, the majority of the questions on the assessments were a type that could be computer scored (e.g., multiple choice or embedded answer). There were three test questions that assessed physiology objectives and one that assessed a biofluids objective that were open-ended and rubrics were created for reliable scoring.

AEP scores were based on the Index of Adaptive Expertise which has previously been used to assess adaptive expertise in various biomedical engineering disciplines (Cordray et al., 2009; Martin et al., 2005; Massa, Dischino, Donnely, & Hanes, 2007; Pandy et al., 2004). Validity and reliability experiments have not been reported for the Index of Adaptive Expertise.

6.7 Discussion

None of the null hypotheses could be rejected. In order to test the effect of physiology content structure and mathematical approach on adaptive expertise, AEP scores, learning gains, and raw component scores were analyzed using univariate ANOVA test. The tests for both content structure and mathematical approach did not reach statistical significance. A second dependent variable, Biofluids Learning Gain, was analyzed using a parametric analysis of variance. The content structure and mathematical approach effects on biofluids learning gain were also found to be statistically non-significant.

Effect size is the strength of the effect an independent variable has on a particular dependent variable; therefore, to interpret the effect sizes, the percent of non-overlap of the scores for distributions of each group was determined using tables for the interpolation of effect size, *d*. Cohen (1988) proposed rules of thumb for interpreting effect sizes: a “small” effect size is .20, a “medium” effect size is .50, and a “large” effect size is .80.

In the analysis of AEP scores, the effect sizes for Content Structure (0.03) and Mathematical Approach (0.18) were quite small. As such, the anticipated overlap for the system-based and content-based content structure distributions was approximately 99 percent. The overlap for the two mathematical approach distributions, qualitative and quantitative, was 92 percent.

The effect sizes were also quite small for the BLG variable. The percentage of distribution overlap for the two content structure distributions was 98% (effect size = 0.05). Similarly, the percentage of overlap for the two mathematical approach distributions was 99% (effect size = 0.02).

Further analysis of the data using regression analysis was not considered because of the small sample size (N=41), the small effect sizes and the results of the post hoc power analysis (Green, 1991). To test the hypotheses using this experimental design, much larger sample sizes would be required. The methods and study protocol used for this experiment are not feasible for sample sizes of that magnitude.

Chapter 7 – Using multiple case study comparison to analyze adaptive expertise

To be submitted as: Nelson, R.K. and Chesler, N.C., 2013. Using multiple case study comparison to analyze adaptive expertise in undergraduate engineering students engaged in online challenge-based learning

7.1 Introduction

The undergraduate education curricula in most engineering disciplines focus on providing students with a foundation in topics critical to the discipline as well as the specific tools and language to solve a specific subset of engineering problems. Upon completion of undergraduate degree programs, individuals are rarely experts in any engineering discipline. Even if routine expertise had been acquired in a specific area, graduates might soon find themselves with new problems to solve with new technologies, thus rendering previous expertise obsolete.

In the interdisciplinary field of biomedical engineering (BME), expertise may be required to cover a wide breadth of disciplines where new technologies are rapidly changing how engineers approach problems. As such, it may be more important to develop students' adaptive expertise than routine expertise in a specific topic. Adaptive expertise differs from routine expertise. Routine experts notice patterns of information and retrieve relevant knowledge from memory more quickly than novices. An expert's performance on tasks often becomes automatic, thus increasing speed and efficiency (Bransford et al., 2000; Chi, Glaser, & Farr, 1988). Adaptive experts are less automatic or routine in their approach to solving novel problems; they instead use their knowledge and experience flexibly in new situations (Hatano & Inagaki, 1986). Individuals with higher levels of this type of expertise are better able to distinguish which rules and principles apply to a problem and adjust their performance accordingly (Gott, Hall, Pokorny, Dibble, & Glaser, 1992).

Adaptive expertise in physiology is particularly relevant for BME students as they use prior physiology knowledge to learn both physiology and biomedical engineering topics. Biomedical engineering students typically take one or two physiology courses early in their undergraduate program. Even in two courses, it is difficult for instructors to cover all of the physiology topics that students will need to know throughout their engineering careers. Successful biomedical engineers will be lifelong learners of physiology. Students with higher levels of adaptive expertise may better use the physiology knowledge gained in the classroom to continue to learn both physiology and engineering topics as they solve the problems that are presented later in the undergraduate curriculum and in their careers.

Five components are particularly important to consider in the development of adaptive expertise in undergraduate engineering students: flexibility, innovation, lifelong learning, metacognition and knowledge efficiency. If the components of adaptive expertise can be effectively measured, learning materials and engineering education best practices that promote the development of adaptive expertise can be assessed, evaluated and improved.

The Index of Adaptive Expertise (AdEX Index) is a metric constructed to operationalize adaptive expertise as a measure of learning gains in factual knowledge, conceptual knowledge and transfer of learning (Pandy et al., 2004; Petrosino et al., 2006). The metric was first developed to quantify adaptive expertise in undergraduate student learning of movement biomechanics using a weighted combination of factual knowledge, conceptual knowledge and transfer to create a single effect size for adaptive expertise.

This study explores the extent to which the AdEX Index predicts the presence of five theoretical components of the adaptive expertise construct in the learning behaviors and perceptions of undergraduate engineering students with scores at various levels on the index. This mixed methods research follows a sequential explanatory design (Creswell, 2003). A preliminary quantitative study is used to assess adaptive expertise in physiology using the AdEX Index metric. An AdEX score was obtained using tests of learning gains in factual and conceptual physiology knowledge along with transfer scores attained as a measure of a student's use of prior physiology knowledge while exploring biomedical engineering topics. Two participants with high scores, one with an average score, and one with a low score based on the AdEX index were purposefully sampled for the qualitative study. Data from each participant's learning record in the preliminary study and interview data that explored the theoretical components of adaptive expertise were analyzed and reported in a comparative case study.

7.2 Related Literature

Adaptive expertise is characterized by a flexible, innovative and creative approach to problem-solving within a specific domain (Hatano & Oura, 2003). In contrast to routine experts who can solve familiar problems with swiftness and ease, adaptive experts use their expert knowledge to invent new ways to approach problems (Holyoak, 1991). The adaptive expertise construct is important to the undergraduate engineering curriculum as it prepares students to work in novel design situations where they must be innovative. In a study of undergraduate design education, adaptive expertise was demonstrated to provide an effective balance of providing opportunities to gain technical proficiency with opportunities for students to apply their knowledge innovatively (McKenna, 2007). Adaptive expertise may best be considered a continuous model where educators help students achieve increasing adaptive performance (Martin et al., 2006)

Schwartz, Bransford and Sears (2005) proposed a developmental model for adaptive expertise. In this model, adaptive expertise can develop along two dimensions: efficiency and innovation. As students grow along the efficiency dimension, they demonstrate increasing ability to quickly retrieve and apply appropriate knowledge to problem-solving tasks. Growth along the innovation dimension is also essential in the development of adaptive expertise as students learn to adapt to novel situations optimally and creatively. In providing learning opportunities to students, it is important to provide a balance along the efficiency and innovation dimensions. Design and problem-solving courses provide opportunities for the study of how these dimensions can develop simultaneously (Svihla, Petrosino, Martin, & Diller, 2009).

Novel design challenges have been used to assess adaptive expertise in undergraduate engineering students (Walker, Cordray, King, & Brophy, 2006). Challenge-based instruction, based on inquiry-driven models, has been shown to help students develop along both a dimensions (Martin et al., 2007). In a study to identify instructional methods that promote early development of adaptive expertise, students who received challenge-based instruction had greater gains in both efficiency and innovation compared to students who received traditional instruction (Martin et al., 2007).

In addition to innovation and efficient use of knowledge, several other elements of the adaptive expertise construct have been postulated. In describing how people learn, Bransford et al. (2000) note that "adaptive experts are able to approach new situations flexibly and to learn throughout their lifetimes. They not only use what they have learned, they are metacognitive and continually question their current levels of expertise." Flexibility, as a unique component of adaptive expertise, evolves from the ability to balance knowledge efficiency and innovation. In developing adaptive expertise, a student may retrieve and effectively apply appropriate knowledge and skills with increasing efficiency but temper this with a willingness to be innovative in the problem-solving approach. Students demonstrating the peak balance of efficiency and innovation are functioning in the *optimal adaptability corridor* (Schwartz et al., 2005). Ultimately, the ability to separate rules that apply to a problem from rules which do not distinguishes adaptive experts from routine experts (Gott et al., 1992).

The continual or lifelong learning aspect of adaptive expertise manifests in the methods adaptive experts use to solve problems. Lifelong learning skills are considered process skills in the engineering education curriculum. Woods (1994) divided the learning process into eight tasks that the lifelong learner must master: 1) sense a problem or need; 2) identify learning issues; 3) create learning goals and assessment criteria; 4) select resources; 5) carry out the learning activities; 6) design a process to assess learning; 7) do the assessment; and 8) reflect on the learning process. With traditional instruction models, the student is typically responsible for only one of these tasks: carrying out the learning activities. In contrast, problem-based instruction allows students to develop all of the lifelong learning processes (Woods, Felder, Rugarcia, & Stice, 2000). In any type of instructional situation, adaptive experts strive to learn more from the instructional experience and from others (Bransford & Schwartz, 2009).

With a theory-building or explanation-testing model, the learner makes a hypothesis and then expands their knowledge to test that hypothesis (Gott et al., 1992; Hatano & Inagaki, 1986). Metacognition is the knowledge and regulation of one's own cognitive functioning (Flavell, 1979). Mindful and deliberate engagement with learning activities contributes to the development of adaptive expertise (Smith, Ford, & Kozlowski, 1997). Adaptive experts demonstrate the ability to monitor their own knowledge and engage in the deliberate practice of reflection and self-explanation of the concepts associated with problem-solving tasks (Chi, 2011; Wineburg, 1998).

In order to promote the development of adaptive expertise in undergraduate engineering students, educators must be able to assess the adaptive expertise construct. Survey techniques have been used to measure associated qualities (Fisher & Peterson, 2001). More directly, adaptive expertise has been assessed with far-transfer problems (Van Lehn & Chi, 2012). Students are presented with novel problems that require them to extend beyond routine problem-solving approaches. These problems may be assessed with dynamic assessment that allows students to access instructional resources (Bransford & Schwartz, 1999; Feuerstein, 1979; Haywood & Tzuriel, 2002). Dynamic assessment is characterized by two opportunities for learning in different task domains. In a first learning period, students acquire knowledge in a domain. Then, in the second task domain, the prior knowledge is monitored and learning gains assessed. When the two task domains are well matched, adaptive experts should master the second domain more efficiently than routine experts.

To arrive at a measure of adaptive expertise, learning gains of factual and conceptual or application questions have been compared to transfer questions (Klein & Geist, 2006). Weighted effects of factual, application and transfer questions have been combined to form an index of Adaptive Expertise (AdEX Index) that follows a linear transformation (see Equation 7-1) (Klein & Geist, 2006; Pandy et al., 2004). Studies have explored different weightings for factual knowledge, conceptual knowledge and transfer; however, the original weightings were maintained and used in later studies of adaptive expertise (Cordray et al., 2009; Petrosino et al., 2006).

$$\boldsymbol{AdEX\ Index} = [(\mathbf{0.10} * \boldsymbol{Facts}) + (\mathbf{0.40} * \boldsymbol{Application}) + (\mathbf{0.50} * \boldsymbol{Transfer})] \qquad \text{Equation 7-1}$$

7.3 Methodology

The goal of this study is to compare the learning behaviors, attitudes and perceptions of undergraduate engineering students with high, average and low scores on the AdEX Index metric. The study explores the alignment of the Index of Adaptive Expertise metric with the theoretical underpinnings of the adaptive expertise construct.

7.3.1 Overview of research methodology

The mixed methods study followed a sequential explanatory research design. A quantitative study of adaptive expertise in physiology was followed by a case study comparison of selectively sampled participants with high, average, and low scores based on the AdEX Index.

The quantitative study explored potential differences in adaptive expertise in physiology and biofluids learning gain scores between engineering students who acquired physiology knowledge via instruction that differed based on presentation structure (system-based vs. content-based) and/or mathematical approach (qualitative vs. quantitative). Through comparative case studies, the qualitative study details the observed and reported learning behaviors of four individuals whose scores on a measure of the AdEX Index placed them at various points along the continuum. This work explores how effective an AdEX Index score is in predicting the presence of absence of behaviors, perceptions and attitudes consistent with the components of adaptive expertise identified in the literature: 1) efficient use of knowledge; 2) innovation; 3) flexibility; 4) lifelong learning skills; and, 5) metacognition.

7.3.2 Preliminary study

The quantitative study followed a 2x2 factorial design with independent groups and Mathematical Approach (MA) and Content Structure (CS) as the independent variables (Figure 7-1). The content was developed into four physiology learning modules aligned with the experimental conditions. To manipulate the Content Structure variable, the lessons in two of the modules followed a system-based taxonomy (i.e., cells, tissues, organs, organ systems) which followed the traditional format of many introductory physiology textbooks (e.g., Levy, Koeppen, & Stanton, 2005; Widmaier, Raff, & Strang, 2006). The lessons in the other two modules were adapted from a concept-based taxonomy proposed for use in the biomedical engineering curriculum (Figure 7-2) (Silverthorn, 2002; Nelson, Strang and Chesler, 2013).

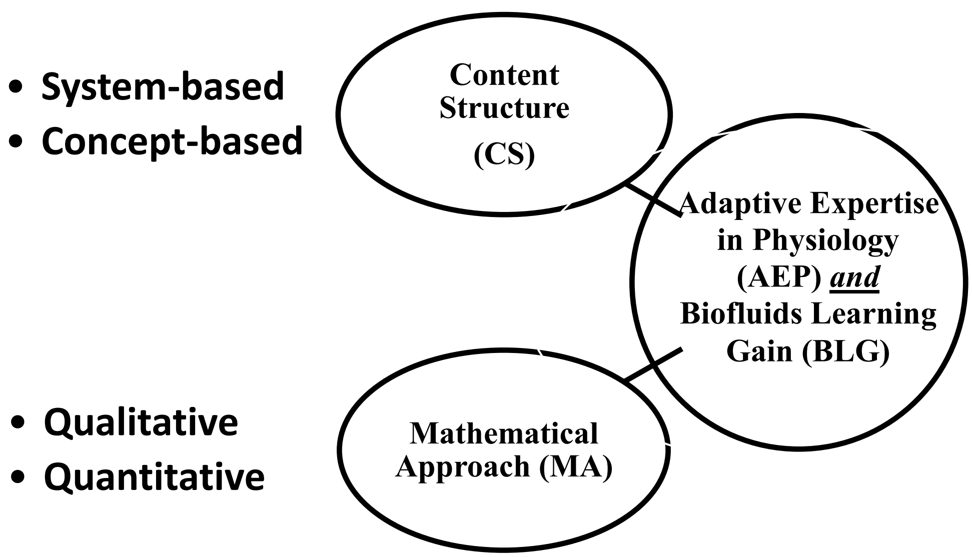


Figure 7-1**.** 2x2 factorial design with Content Structure and Mathematical Approach as independent variables and Adaptive Expertise in Physiology and Biofluids Learning Gain assessed as dependent variables.

To incorporate the Mathematical Approach variable, in one of the system-based learning modules only qualitative descriptions of physiology content were used. In the quantitative learning modules, algebra, calculus and other mathematical representations were used to explain physiology content where appropriate. The experimental learning modules presented the same physiology content in four different formats: qualitative, systems-based (QLSB); qualitative, concepts-based (QLCB); quantitative, systems-based (QTSB); and quantitative, concepts-based (QTCB).

Form	•Levels of Organization in the body; Compartmentation
Function	•Structure/function relationships; Molecular interaction; Biological energy
Physical Properties	•Mechanics: movement and forces, Elastic properties, Bioelectricity, Emergent properties of complex systems
Variables and Measurement	Structure/function relationships; Molecular interactions; Biological energy
Information Processing	•Biological transduction; Communication and coordination
Control Systems	•Homeostasis/Dynamics & Control systems; Mass flow (transport); Mass balance; Heat balance
Pressure Flow Resistance	•Pressure - Flow - Resistance

Figure 7-2**.** Concept-based lessons and topics derived from a taxonomy proposed for the undergraduate biomedical engineering curriculum(Silverthorn, 2002; Nelson et al., 2013).

Two dependent variables were measured: Adaptive Expertise in Physiology (AEP) and Biofluids Learning Gain (BLG). Adaptive Expertise in Physiology was directly calculated as an AdEX Index score using a linear combination of factual knowledge, conceptual knowledge and transfer. The factual knowledge and conceptual knowledge elements were assessed as pre/post learning gains associated with the physiology learning modules and the transfer component was measured as students engaged in a subsequent challenge-based biofluids learning module where the physiology learning objectives were re-assessed in a new context.

7.3.2.1 Materials and instrumentation

To assess the dependent variables, the study participants were provided with an opportunity to use their new physiology knowledge in a novel context as they solved an engineering challenge problem centered on topics in biofluids. The biofluids learning modules were developed as challenge-based learning following the STAR.Legacy cycle (Klein & Harris, 2007; Schwartz et al., 1999). These online, dynamic learning modules provided an environment where study participants could apply physiology knowledge as they collaboratively worked to solve a biofluids challenge problem.

In each of the four learning modules, the same seven learning objectives were evaluated to assess pre/post student learning. Although the general learning objectives were representative of the physiology content in all four physiology learning modules, the specific learning objectives for the system-based and concept-based physiology modules were adjusted slightly to match the emphasis of these unique experimental conditions (see Table 7-1). Using the Moodle™ course management system, the physiology lessons were created as online lessons that could be completed by the student participants independently. Each lesson was designed for approximately 30-45 minutes of student engagement time.

TABLE 7-1. Learning objectives and lesson names for the system-based and concept-based physiology modules.

System-based Learning Objectives		Concept-based Learning Objectives	
CELLS	Recognize the main points of cell theory	**FORM**	Summarize function of the blood-brain barrier
TISSUES	Compare and contrast the structure and function of the four major tissue types	**FUNCTION**	Illustrate how structure and function of body tissue are related
HEART	Predict change in blood flow related to heart valve insufficiency	**PHYSICAL PROPERTIES**	Differentiate blood vessels based on their elasticity Identify the gases that interact with the hemoglobin molecule in the process of respiration
BLOOD	Identify a normal hematocrit value for a healthy adult male Cite examples of the function of blood	**VARIABLES AND MEASUREMENT**	Identify a normal hematocrit value for a healthy adult male
VESSELS	Differentiate blood vessels by function Assess effects of capillary filtration given changes in typical pressures	**INFORMATION PROCESSING**	Utilize understanding of biological transduction to recognize type of feedback employed by central chemoreceptors to affect respiration Recognize homeostasis as a main point of cell theory
LUNGS	Recognize that a pressure gradient is required for respiration	**CONTROL SYSTEMS**	Assess the effects of capillary filtration given changes in typical pressure Recognize a pressure gradient is needed for mass transport
CNS	Summarize function of the blood-brain barrier Trace the central chemoreceptor feedback process that affects respiration	**PRESSURE** **FLOW** **RESISTANCE**	Predict change in blood pressure related to narrowing of path given volume information

To evaluate the transfer of physiology knowledge, the general physiology learning objectives were assessed within the biofluids challenge modules with seven questions that matched the questions on the physiology pre/post tests. These transfer assessment questions were included as review questions that the study participants answered after they completed each of the four biofluids lessons. To provide an assessment of biofluids learning gain, eight engineering objectives were evaluated with a pre/post assessment at the beginning and end of the participant's interaction with the biofluids challenge module.

Similar to the physiology modules, the biofluids online learning environment was created using the Moodle™ course management system. Additionally, a virtual conference room was created in Second Life® (see Figure 7-3). The online environment was set up so that students could use their new physiology knowledge as they collaborated with peers to solve an engineering challenge problem. Using the Moodle™ course page as a structuring tool, it was possible to guide the study participants through each phase of the SL Cycle. The Second Life® conference room was used for synchronous collaboration by each team.

The biofluids challenge modules were developed around two challenge questions that involved understanding of similar biofluids topics. Half of the groups explored a question related to Giraffe Hemodynamics and the other half considered the Human Limitations of Deep Diving. The same eight biofluids learning objectives were the foundation of the four lessons in the both challenge modules (see Table 7-2).

Figure 7-3. Virtual conference room in Second Life® multi-user virtual environment

TABLE 7-2. Lesson names and learning objectives for the biofluids challenge modules.

Giraffe Lesson/ Diving Lesson	**Learning Objectives**
Giraffe Cardiovascular System Basics/ An Introduction to Deep Diving	• Define hydrostatic pressure • Apply hydrostatic pressure equation to make predictions
Scaling and Cardiovascular Anatomy	• Define allometric scaling • Explain how dimensional analysis could be used to solve a problem
Capillary and Cerebral Perfusion	• Describe transmural pressure and its relationship to absolute pressure • Apply LaPlace's Law to interpret physiological changes
Cerebral Blood Flow	• Recognize equations that model biofluid flow • Differentiate between Newtonian and non-Newtonian biofluid flow

7.3.2.2 Participants

The study was not affiliated with any university course; instead, first and second year undergraduate engineering students at a US research university were recruited via posters in the campus engineering library, announcements at meetings of student organizations, and mass email to targeted engineering course rosters. Although the study could be completed from any location with Internet access at any convenient time, participation required a ten to twelve hour time commitment. While forty-eight participants were originally recruited, only forty-one completed the study, 25 males and 16 females. All participants had completed or were in the process of taking their second college-level calculus course and none had taken a college-level or high school advance placement physiology course. The study was conducted with approval of the university's Institute Review Board and participants who completed the study were paid $100.

7.3.2.3 Experimental procedure

Participants were assigned, as recruited, to teams of three students. Eight teams were assigned to consider the Giraffe Hemodynamics challenge question and eight teams explored the Deep Diving challenge question. Additionally, within each biofluids challenge module, two teams were assigned to each of the four experimental physiology training conditions: QLSB, QLCB, QTSB, and QTCB. Study procedures were explained and login instructions were provided in an initial individual meeting with each participant. After this meeting, all of the remaining study activities were completed by the participant remotely with an Internet connection.

To begin the learning activities the students were instructed to view the challenge question online and then complete the seven physiology lessons as self-paced independent learning. Student progress was tracked and when all of the team members had finished the physiology lessons, a team meeting was scheduled in the Second Life® conference room to brainstorm solutions to the challenge question. The brainstorming sessions were moderated by a peer facilitator who was a member of the research team. Like the participants, he appeared as an avatar (male) in the Second Life® virtual world. His role was to start the meeting and answer any process questions. The peer facilitator had a limited role and did not answer content questions or otherwise help with the development of a solution to the challenge.

After the brainstorming session, the participants independently completed a series of lessons on biofluids topics related to the challenge. Students were encouraged to seek multiple perspectives and research their initial ideas. In addition to the lesson material, the biofluids learning modules included an online resource library of articles related to the challenge questions. To facilitate their teamwork outside of the virtual world meetings, students were provided with asynchronous online collaboration tools including a discussion forum and wiki. Participants used the wiki to collectively draft their final proposed solution during a second facilitated meeting in the virtual conference room. After the teams submitted their final solution, each member individually completed a debriefing survey and a biofluids post-test with questions comparable to the pre-test completed before the first team brainstorming meeting.

7.3.2.4 Data analysis and metrics

Student learning was evaluated using pre/post assessments for both the physiology and biofluids learning objectives. The pre/post assessments, lesson scores, and review question scores were collected for each participant. The data were used to calculate the two dependent variables of interest: Biofluids Learning Gain (BLG) and Adaptive Expertise in Physiology (AEP).

The BLG score was a learning gain calculated directly from the results of the pre/post assessment. The calculation of the AEP score was based on the transformation associated with the AdEX index (see Equation 7-1) which derives a single effect size by weighting the results of pre/post questions of factual knowledge and conceptual knowledge and the transfer questions related to the same content (Cordray et al., 2009; Pandy et al., 2004).

To calculate the AEP score, the questions on the physiology pre/post assessment were divided into factual knowledge and conceptual knowledge questions. A learning gain score was calculated for each type of question. The transfer component of the AEP score was determined by calculating the learning gain between the combined physiology post-test score (factual and conceptual) and the score the student achieved when the questions were again presented in the biofluids challenge module.

7.3.3 Preliminary study results and case study sample selection

The four participants for the qualitative case study were selectively sampled from the population of students who completed the quantitative study. The AEP scores for all participants were plotted along a continuum of low to high AEP scores (Figure 7-4). Two participants were selected from the group of students whose scores fell near the upper quartile. One participant was selected from near the lower quartile scores and one participant was selected from the scores around the mean. To provide the widest range of experiences, one participant was selected from each of the experimental conditions, QLSB, QLCB, QTSB and QTCB. Participant No. 2 (Y.S.) was selected based on her low AEP score. Participant No. 47 (R.F.) was selected based on his average AEP score. Participant No. 9 (K.F) and Participant No. 42 (S.A.) were selected for the case study comparison as a result of their high AEP scores.

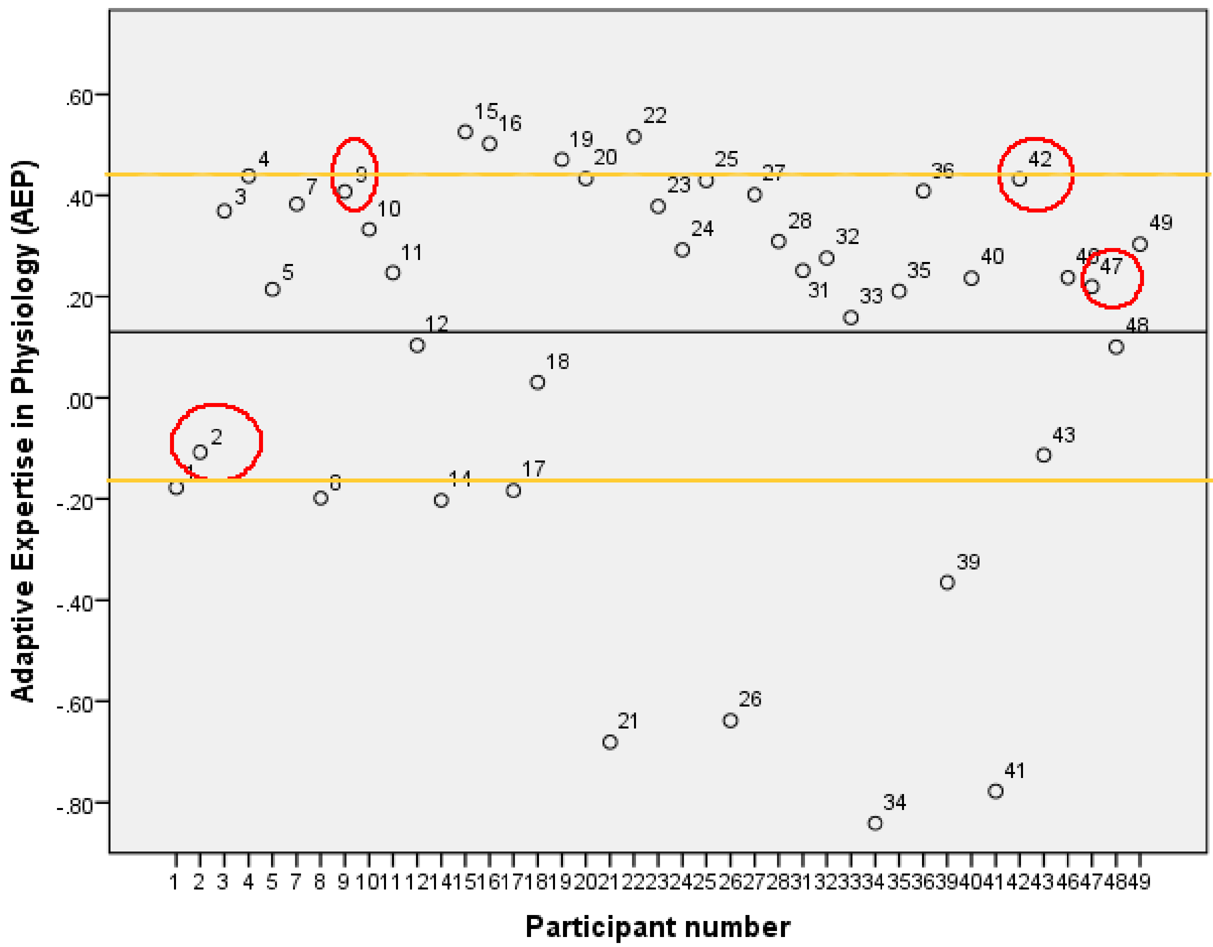


Figure 7-4. Scatterplot of Adaptive Expertise in Physiology (AEP) scores by study participant number with participants selected for the qualitative study circled in red. The black line marks the mean and the yellow lines mark the first standard deviation in the positive and negative direction.

7.4 Multiple Case Study

A directed qualitative content analysis was used to systematically identify themes in the data related to the five components of adaptive expertise. Data were collected from the learning records of four participants selectively sampled from the pool of participants who completed the quantitative study. Directed qualitative content analysis uses existing theory to guide data coding (Hsieh & Shannon, 2005). The data of the one individual with AEP scores near the lower quartile (Y.S.), one near the mean (R.F), and the two individuals with AEP scores near the top quartile (K.F. and S.A.) were further analyzed and combined with interview data as part of a multiple case study comparison.

7.4.1 Participants

Demographic data and the experimental setting for the case study participants are reported in Table 7-3. The analysis of the online learning records from the preliminary study and the interviews conducted as part of the qualitative case study were completed with the approval of the university Institute Review Board. Each participant was compensated $100 for their time.

TABLE 7-3. Demographic data and experimental setting for case study participants

	P1	*P2*	*P3*	*P4*
Avatar identity	Y.S.	R.F.	S.A.	K.F.
Experimental Condition	QLSB	QTCB	QLCB	QTSB
Biofluids Challenge	Giraffe	Diving	Diving	Giraffe
Gender	F	M	F	M
Age	20	18	19	21
Semester classification	2	2	2	3
Major	Biomedical Engineering	Biomedical Engineering	Civil Engineering	Civil Engineering

7.4.2 Experimental procedure

With permission from the university's Institute Review Board, the data from the preliminary study was collected for the selected participants. In an approximately 60-minute interview, each participant was asked questions related to the preliminary study activities, in particular, and a series of general questions about how they typically approach learning (see Appendix L for complete semi-structured interview schedule).

7.4.3 Data analysis and metrics

The learners' experiences with the physiology and biofluids challenge learning modules in the Moodle™ course management system were documented with activity reports and logs that were reviewed as part of the content analysis. The complete transcript for each participant's group meetings in the Second Life® conference space was also analyzed, as was the transcript from the interview about learning approach.

The dataset collected from each participant's online record of engagement with the physiology training and challenge activities was extensive. These documents represent data collected as each participant engaged in the physiology lessons and challenge-based engineering learning activities. The Moodle™ course management system allowed the tracking of the amount of time a participant engaged with a course activity, the number of attempts at a quiz or lesson, as well as quiz and lesson scores. Including the chat and interview transcripts, nine documents were analyzed for each participant.

The nine data records were analyzed in a two-step process using the ATLAS/ti software package as a tool for data management and analysis (Scientific Software Development, 2012). In the first step, the documents were reviewed and coded for important moments or events associated with the learning process. On this first review, segments of the documents were labeled to highlight key learning events. For instance, a review of the Moodle™ physiology activity log might show that a participant clicked on the link that opened the glossary. Additionally, by examining the Activity Log it could be noted that this participant viewed one specific word in the glossary eight times. These two events would be coded as "global glossary view" and "repeated glossary word views." In the initial coding process, the focus was on identifying and labeling unique learning events. Through this process a list of codes was developed for learning events observed in the documents (see Table 7-4). The documents for each participant were examined with the complete list of codes for consistency in notation of observed events.

TABLE 7-4. Codes developed during analysis of learning records [#,observed; @,user-reported]

#early wiki view	**#predict viable concepts**
#edit wiki	**@use of outside Internet resources**
#experimenting with LMS	**#global glossary view**
#extended resource view	**#use of outline**
#extensive use of resource library	**#repeated glossary view**
#forum post	**#resource library view**
#forum post review	**#resource library multiple views**
#glossary view	**#short lesson engagement**
#use of interactive tool	**#short quiz engagement**
#learning objective view	**#simultaneous lesson and quiz view**
#lesson view during post-test	**#simultaneous lesson and wiki view**
#<u>limited</u> use of resource library	**#create wiki**
#long lesson engagement	**#chat transcript review**
#long quiz engagement	**#user profile view**
#multiple resource views	**#video view**
#multiple lesson attempts	**#wiki view**
#multiple lesson objective views	**@biofluids lessons most valuable**
#multiple quiz attempt	**@discussion forums valuable**
#multiple start	**@discussion with team most valuable**
#<u>no</u> lesson objective views	**@MUVE not valuable**
#<u>no</u> mention of physiology systems	**@MUVE valuable when F2F not possible**
#<u>no</u> physiology text views	**@perceived biofluids learning gain**
#<u>no</u> resource library views	**@perceived <u>no</u> transfer of knowledge**
#<u>no</u> video views	**@perceived physiology concept learning gain**
#physiology text view	**@perceived physiology system learning gain**
#predict cardiovascular system	**@perceived transfer of knowledge**
#predict CNS	**@resource library most valuable**
#predict respiratory system	**@wikis valuable**

In the second step of the analysis process, the coded events were grouped according to five thematic components of the adaptive expertise construct: 1) knowledge efficiency; 2) innovation; 3) flexibility; 4) lifelong learning skills; and 5) metacognition. Some events were aligned with more than one adaptive expertise theme (see Table 7-5).

TABLE 7-5. Learning Event Codes grouped by adaptive expertise components

Adaptive Expertise themes and Associated Learning Observations		**Codes used in Quantitative Analysis (#observed in record; @reported by user)**
FLEXIBILITY		
	Wiki use	#early wiki view #create wiki #edit wiki @wikis valuable
	Discussion Forum use	#forum post #forum post review @discussion forums valuable #no forum use
	Resource Library use	#resource library multiple views #limited resource library use @resource library valuable #resource library view
	Multiple Lesson attempts	#multiple lesson attempts
	Perceived Transfer of Knowledge	@perceived transfer of knowledge @perceived no transfer of knowledge @perceived physiology systems/concepts learning gain #systems/concepts predictions
INNOVATION		
	Simultaneous views	#simultaneous lesson/quiz view #simultaneous lesson/wiki view
	Use of new technology	#forum add post #forum post review #chat transcript review #use of outside Internet resources #no forum use
LIFELONG LEARNING		
	Experimentation	#experimentation with LMS #use of interactive tool
	Resource use	#glossary view #video view #text view #extensive use of resource library @resource library most valuable
METACOGNITION		
	Multiple views	#multiple quiz attempts #multiple lesson attempts #multiple resource views #repeated glossary views #no multiple quiz attempts

		#no multiple lesson attempts
	Advance organizers	#view learning objectives #global glossary view #multiple lesson objective views #use of outline
	Perceived learning	@perceived transfer of knowledge @perceived no transfer of knowledge @perceived physiology systems/concepts learning gain
KNOWLEDGE		
	Prediction of useful content knowledge	#predict systems/concepts

7.4.4 A model of adaptive expertise

7.4.4.1 Knowledge efficiency

When they encounter new problems, adaptive experts can retrieve and apply prior knowledge efficiently. This efficiency is marked by not only speed, but accuracy. For example, the Moodle™ activity reports of participants with high levels of adaptive expertise should show a pattern of high scores and short engagement times on review quizzes.

7.4.4.2 Innovation

Adaptive experts are innovative. As they learn new concepts, they may freely modify existing methods or invent new ways to accomplish a goal. Individuals with high levels of adaptive expertise may realize that there are multiple ways to solve a problem and may approach the same problem with different solutions. Students with high levels of adaptive expertise may demonstrate the ability to use technology in innovative ways as they engage in learning activities. Innovation may be demonstrated when the student uses artifacts of online learning that would not exist in the traditional setting. For example, the chat transcripts from both of the meetings in Second Life were available for student review. An adaptive expert might review these transcripts reflecting an innovative way of using the online tools to replace old ways of learning.

7.4.4.3 Flexibility

Adaptive expertise is characterized by flexibility. An adaptive expert will show evidence of adapting or changing an initial understanding or misunderstanding of a concept. As an adaptive expert learns new concepts, they continue to mold their current understanding to fit or adapt new information. A resource library was provided for participants to use to build their knowledge on the challenge topic. None of the articles were required reading, yet they were easy to access and could be accessed multiple times. Multiple access of the same resource may indicate adaptive understanding of a topic or concept. The learner may recognize that a second review of a text can provide knowledge that shapes earlier understanding of the same material.

7.4.4.4 Lifelong learning skills

Adaptive experts value the concept of lifelong learning and demonstrate interest in continual learning. Two key components of lifelong learning are "continual process" and "self-motivation." An adaptive expert will recognize that there is always more to learn and initiate the process of learning more. Individuals with high levels of adaptive expertise will approach tasks with a knowledge-seeking focus. Experimenting with the learning management system, Moodle™ to see how the software works (beyond the functions specifically required for class use) is an example of self-motivated knowledge-seeking.

7.4.4.5 Metacognition

Adaptive expertise is associated with high degrees of metacognition and the ability to monitor one's own knowledge level. Individuals with high metacognitive abilities possess knowledge about when and how to use particular strategies for learning or for problem solving (Metcalfe & Shimamura, 1994). An advance organizer is information presented to students before learning takes place that can be used to organize and interpret the incoming learning materials (Mayer, 2003). As an example of metacognition, viewing lesson learning objectives may reflect a student setting the stage to know what they need to learn during a lesson to achieve an adequate knowledge level.

7.4.5 Four case studies

The following case studies report quantitative and survey data obtained from the preliminary study in addition to results from the interviews and qualitative content analysis related to the adaptive expertise themes. The first case study introduces Y.S., a student with low AEP scores. The second study describes the learning behaviors of R.F., a student with AEP scores near the mean. Finally, the last two studies present two individuals, K.F. and S.A., with high AEP scores. The five theoretical components of the adaptive expertise construct guide the case study reports.

7.4.5.1 Case 1 – Y.S.

Y.S. is a female undergraduate student in her second semester with plans to major in Biomedical Engineering. She was assigned to the QLSB condition and was teamed with two other participants to complete the Giraffe Hemodynamics challenge. Y.S. completed the physiology pre-test with a score of 30.7%. She began the first of seven lessons one week after taking the pre-test and completed the lesson and the review quiz before closing her online session. She completed Lesson 1 in just over 45 minutes (45:32) and immediately opened the review quiz and scored 92.86% completing the multi-part four question quiz in approximately three minutes (2:58).

This participant followed a similar pattern for the remaining six physiology lessons. Y.S. only reviewed one of the seven physiology lessons (Lesson 5) a second time. After completing Lesson 6, she returned to Lesson 5 and reviewed it in five minutes while simultaneously answering the questions on the Lesson 5 quiz. Y.S. only repeated one review quiz (Lesson 2). After scoring 83.33%, she immediately retook the quiz and scored 100%. The overall average physiology lesson engagement time for this participant was just less than 45 minutes (44:42) which was among the highest for any participant completing the preliminary study. The time that Y.S. spent on each review quiz was also higher than most of the preliminary study participants. Her average engagement time was 08:29 minutes and her average score on the physiology review quizzes (averaging all multiple attempts) was 79.21%. Y.S. scored 79.3% on the physiology post-test.

Y.S. approached the four biofluids lessons in a similar fashion. She reviewed each lesson only one time with an average lesson engagement time of just less than 22 minutes (21:56). This engagement time was among the highest average times among all of the preliminary study participants. Y.S. did repeat two of the four review question sets for the biofluids lessons. She repeated the review questions for Lesson 1 once and repeated the review questions for Lesson 3 two times. Her average score on the biofluids review quizzes was 85.23% and her average time per quiz was almost four and a half minutes (4:23). Y.S. had a pre/post learning gain of 16.6% for the biofluids learning module. She scored 43.8% on the pre-test and 53.1% on the post-test.

Although Y.S. did view the overall course objectives for the physiology training module, she rarely viewed the lesson objectives before beginning either the seven physiology lessons or four biofluids lessons. She only viewed the lesson objectives for the first two physiology lessons. Another feature that Y.S. used was the linked glossary. Y.S. clicked on nine highlighted words to access the glossary definition throughout her interaction with the lesson modules. She had seven unique glossary views during the physiology lessons and two unique views during the biofluids lessons. While engaging with the interactive physiology modules, Y.S. did not view any of the videos and only viewed one physiology reference text. While completing the biofluids challenge module, she did not view any of the resource library articles. She did, however, review the chat transcript from the brainstorming meeting while she was working on the final solution using the team wiki. In addition to the wiki, Y.S. viewed posts on the discussion forum, although she, herself did not post anything.

On the measure of Adaptive Expertise in Physiology, Y.S. had a score of -0.11 which placed her near the lowest quartile on this measure of adaptive expertise.

7.4.5.2 Case 2 – R.F.

R.F. is a male first-year undergraduate student pursuing a major in Biomedical Engineering. For the preliminary study, he was assigned to the QTCB condition and the Deep Diving challenge. R.F. scored 23.6% on the physiology pre-test. He completed the first physiology lesson on the same day he took the pre-test in just over twenty minutes (20:40) and completed the review questions in less than two minutes (1:33). His score on the review quiz was 92.31%. R.F. immediately repeated the review quiz and scored 100%.

R.F. continued the pattern of repeating review quizzes for the physiology lessons. He averaged two attempts on each lesson review quiz. By comparison, he only completed each of the biofluids lesson review quizzes one time, even though he had a perfect score on only two of the four quizzes. The average length of time that R.F. took to complete a physiology review quiz was about three minutes (3:07). His average completion time for the biofluids quizzes was 01:29. R.F. did not repeat any lessons in either the physiology or biofluids modules. His average completion time was approximately 22 minutes (22:25) for the physiology lessons and 14 minutes (13:58) for the biofluids lessons. His average score for the physiology lessons was 78.33% which was higher than his average score on the biofluids lessons (59.79%). This participant scored 49.3% on the physiology post-test.

While engaging with the physiology lesson material, R.F. viewed the learning objectives for six of the seven lessons and opened the learning objectives for Lesson 4 three times. He also occasionally opened the lesson material while completing a review quiz. Beyond these uses of the course management system, he did not take advantage of any of the interactive features in the physiology lessons. R.F. did not use the glossary feature while working on the physiology lessons, but he looked up one word while completing the biofluids lessons. He did not reference any of the additional physiology text or look at any of the videos in the lessons. In the quantitative experimental condition, one lesson contained an interactive simulation tool that allowed the student to explore the effect of changing various parameters on the calculation of the oxyhemoglobin dissociation curve. Although R.F. clicked the link to open this interactive tool, he returned to the lesson text after seven seconds. While working on the biofluids challenge module, R.F. did look at two of the articles in the resource library, one of them on two separate occasions. In a debriefing survey, when asked which activity he felt was most valuable in solving the challenge question, he chose the response “Resource Library was most valuable.” R.F. did review the chat transcript after the brainstorming meeting. He also posted in the discussion forum and viewed responses in the forum. R.F. had a learning gain (36.4%) on the assessed biofluids learning objectives. His pre-test score was 31.3% and his post-test score was 56.3%.

On the assessment of adaptive expertise, R.F. had an Adaptive Expertise in Physiology score of 0.06 which placed him at around the mean of the scores for all participants.

7.4.5.3 Case 3 – K.F.

K.F. is a 2nd year student with intent to major in Civil and Environmental Engineering. He was assigned to the QTSB condition and completed the Giraffe Hemodynamics challenge. K.F. scored 30.7% on the physiology pre-test. He did not review the learning objectives for any of the physiology lessons. He completed the first lesson in approximately twenty minutes (20:48) and immediately took the review quiz. He finished the quiz in just over one minute (1:09) and scored 80% on this quiz. K.F. immediately repeated the quiz and scored 96.6%. He had the quiz open for about 22 minutes (21:36) as he made his two scored attempts. During this time, he also had Lesson 1 open. K.F. repeated the process of having the review quiz and lesson open simultaneously for all of the physiology lessons.

In the physiology modules, K.F. only reviewed Lesson 3 a second time. After repeating the review quiz for Lesson 1, he also did the review quiz for Lesson 2 a total of three times. His average score for the lesson review quizzes was 90.64%. The average time spent on each quiz was 8:41 and the average time he engaged with each physiology lesson was 19:33. K.F. had a physiology post-test score of 62.9%.

Although K.F. did not look at any of the physiology supplemental text material, he did view three of the videos in the physiology lessons. He did not view any of the learning objectives for the physiology lessons, but he did view one of the learning objective documents for a biofluids lesson. K.F. did click on the link for the interactive oxyhemoglobin dissociation curve simulation tool, but he only stayed at the site for 41 seconds. While interacting with the physiology lessons, K.F. used the glossary links to find the definitions for five unique terms.

K.F. spent about the same amount of time with the lessons and quizzes in the biofluids module as he did with all the physiology lessons. He completed the first biofluids lesson two times, then each subsequent lesson only once. His average engagement time for the biofluids lessons was 8:44. He repeated all but the first review quiz, spending approximately five and half minutes (5:32) on each quiz attempt. His average score for the quizzes was 76.42%. While completing the biofluids lessons, K.F. continued his practice of having the lesson and quiz open simultaneously. This participant also demonstrated a learning gain (60.12%) for the biofluids learning objectives going from a pre-test score of 53.1% to a post-test score of 81.3%.

K.F. indicated that he thought the resource library was most valuable for solving the challenge. He used the resource library to view nine articles a single time and seven additional articles more than one time. K.F. returned to view the chat transcript after the brainstorming meeting. K.F. used the wiki and posted in the discussion forum, but he did not use the glossary.

K.F. had an AEP score of 0.36 placing him near the upper quartile of participants in the preliminary study.

7.4.5.4 Case 4 – S.A.

S.A. is a first-year engineering undergraduate student with plans to major in Civil and Environmental Engineering. She was assigned to the QLCB experimental condition and worked on solving the Deep Diving Challenge. S.A. scored 52.1% on the physiology pre-test. She glanced at the global learning objectives document for the entire physiology training module (7 seconds) before she took the pre-test.

S.A. started the physiology lessons the day after she completed the pre-test. She reviewed the learning objectives documents for the first two physiology lessons. She reviewed the first lesson two times. Her combined time for these reviews was just over thirty minutes (32:06). S.A.

completed the Lesson 1 review quiz right after she closed the lesson. She finished the quiz in just over one minute (1:09) and scored 33.33% on this quiz. S.A. did not repeat the quiz. In fact, she only repeated one quiz (Lesson 3). Her average time on the quiz attempts was 4:32 and her average quiz score was 83.33%.

The average amount of time S.A. spent on each physiology lesson review was approximately 14 minutes (14:08). S.A. reviewed three lessons two times. She also made use of the ability to simultaneously open a lesson and the review quiz. During these lesson reviews, S.A. made extensive use of the physiology glossary. She viewed the definition of 40 linked words or concepts. She also viewed two of the supplementary readings and viewed two videos. S.A. had a lower physiology post-test score than pre-test score. Her post-test score was 27.1%, which was lower than her pre-test score.

She followed a similar pattern for completing the biofluids lessons. S.A. did not review any of the biofluids learning objectives. She completed each biofluids lesson one time with an average completion time of approximately 19 minutes (18:51). She repeated only one review quiz (Lesson 3). Her average time for each review quiz attempt was just over six minutes (6:04) and her average score was 93.56%.

S.A. continued to use the glossary in the biofluids module. She looked up ten linked words. She also viewed six articles in the resource library. S.A. started the wiki for her group and while she was working on the wiki, she had lessons open for simultaneous viewing. Although she accessed the discussion forum, she did not post anything. She did not access the chat transcript that was available after her team's brainstorming meeting.

S.A. showed a learning gain (57.6%) from the pre-post assessment. Her biofluids pre-test score was 18.8% and her post-test score was 65.6%. Her Adaptive Expertise in Physiology score was 0.38 which placed her near the upper quartile of scores.

7.4.6 Adaptive expertise case comparison

Adaptive expertise develops with time and experience. When comparing participants with varying AEP scores, there is not a clear distinction between levels of adaptive expertise. It is possible, however, to compare and contrast some of the learning behaviors, attitudes and perceptions of undergraduate students who have scores at various points along the Index of Adaptive Expertise. We use the within-case description of each participant to compare the development of the five components of adaptive expertise.

7.4.6.1 Knowledge efficiency

A growth in knowledge efficiency occurs as students are able to quickly retrieve and apply what they know to problem-solving tasks. In the learning module data, the quiz score and timing data may provide insight on developing knowledge efficiency. From a timing perspective, there are not large average differences between the students; however, the participants with higher AEP scores had higher average physiology and biofluids review quiz scores.

To assess potential transfer of physiology knowledge, the participants were asked the following survey question: “If you were asked to solve another engineering challenge involving physiology, how confident would you be if the topic was related to an organ system that was not covered in the physiology lessons?” Of the four participants, only one individual (K.F.) indicated that they were “confident” or “somewhat confident.” The ability to apply prior physiology knowledge appropriately to a novel challenge may indicate a higher level of adaptive expertise.

The amount of time that Y.S. (low AdEX) engaged with the online physiology lessons (5 hours, 13 minutes) was the most of any participant in the preliminary study. The pace of instruction (whether facilitated or self-paced) may also affect levels of knowledge efficiency. In the interviews, several of the respondents mentioned the pace of instruction:

> *"My most favorite class…had a lecture where you kind of learn about different types of engineering and then you're in a lab where you're actually designing something… I like learning in the big lecture hall where it keeps moving, but in a smaller setting you can talk with your classmates and kind of brainstorm and think about it a little bit more."* [S.A.]

> *"Online…you can go at your own pace. If you miss a concept, you can go back and relisten to it…one of my classes the notes are all provided. You just sit, maybe take a supplemental note, but a lot of it is just absorbing the material instead of cramming every detail down without knowing what is going on."* [K.F.]

> *"I like a faster pace. I usually pick up on ideas pretty well. I sort of get distracted and lose concentration when it's dragged out for a long time. That affects my performance, I suppose."* [R.F.]

> *"For me, personally, repetition is really important. In bioinstrumentation [we make] circuits every single lab, whether it's the same type of circuit or different circuits with different components. I don't have a photographic memory, so that's really important for me I found out."* [Y.S.]

7.4.6.2 Innovation

Adaptive experts will modify what exists or create new ways to accomplish a goal. In online or blended courses which use instructional technologies, there are usually many ways to accomplish learning goals. As students become more familiar with online technologies, they recognize the innovative ways that course management systems can be used to assist their own learning. Having a quiz and lesson window open simultaneously is a modification of the existing "open book/note quiz" assessment pattern. Likewise, viewing the online wiki and lesson material in different windows or frames at the same time demonstrates use of all of the tools and resources at hand. All of the participants used the features of the Moodle™ course management system to view two activities simultaneously. S.A. was the only participant to have the wiki and a lesson open at the same time, while K.F. made extensive use of the ability to open the lesson while answering the review questions. Technology allowed the transcript from the brainstorming session in the Second Life® conference room to be accessed by group members immediately following the meeting. All of the participants except S.A. took advantage of having this artifact available to review.

In the interviews, both S.A. and K.F. (high AdEX) indicated their use of technology to solve problems:

> *"There's a pretty straight-forward college student try – you Google it. I've had instances where Google Scholar couldn't even come up with a good argument, so you straight* [sic] *Google and eventually after a time of doing this you learn how to filter out what you want out of Google."* [K.F.]

> *"I'm a big Googler, so I will usually look up what I don't know… And, I try to find like university websites. A lot of professors will put powerpoints up. So, maybe if my professor doesn't, maybe someone from another university will."* [S.A.]

7.4.6.3 Flexibility

Individuals with high levels of adaptive expertise should be able to adapt or change an initial understanding or misunderstanding of a concept. Throughout the physiology and biofluids learning modules, the participants had many opportunities to mold their current understanding to fit the new information. The frequency with which a participant engaged with the wiki and the discussion forum may indicate recognition that knowledge is dynamic. As a learner gathered new information related to the challenge problem and the potential solution, they could immediately share it with the group and build new knowledge collaboratively using the wiki or discussion forum. S.A. and Y.S. started the wikis for their group; however all four participants contributed to their group's final report on the wiki. R.F. and K.F. posted on the discussion forum. All four participants viewed forum posts, even if they did not contribute.

A resource library was provided for participants to build their knowledge on the challenge topic. Although none of the articles were required reading, they were easy to access and could be accessed multiple times. The access of a single article multiple times may be indicative of adaptive understanding of a topic or concept. The learner may recognize that a second review of a text can provide knowledge that shapes earlier understanding of the same material. K.F. [high AdEX] viewed seven articles more than once and R.F. [mid AdEX] viewed two articles multiple times. Although S.A. [high AdEX] viewed many articles in the resource library, she only reviewed them one time. Y.S. [low AdEX] viewed no articles in the resource library.

Taking advantage of collaborative opportunities can be an example of flexibility in learning. Two of the participants specifically talked about the benefits of working a group to design and/or co-construct knowledge. They both reflect on the ways to learn from others in the group.

> *"We have these design projects and we can work with a partner. And, I feel like with me and my partner it's worked out well because we both have different strengths – really different strengths, and that's helped us because we can divide the work more easily. And then also we argue [with] each other, which I think is good because then it's not just one person controlling the whole thing, and it makes everyone double-check themselves and it really makes sure that it's a good thing that's created."* [R.F.]

> *"Typically I try to research as much information that's relevant to the project and then my teammates and I will compare notes on what we find. We'll discuss things. Talk about what we already know that's prior knowledge. Find people we know who can help us…Talk to them and then try to collectively bounce back information…Typically the groups that I had were really good about explaining what we were doing, where we were coming from, and out idea behind something."* K.F.]

7.4.6.4 Lifelong learning skills

The concepts of lifelong learning and self-directed learning are important components of adaptive expertise. Adaptive experts demonstrate interest in continual learning. An adaptive expert will recognize that there is always more to learn and initiate the process of learning more. Individuals with high levels of adaptive expertise will approach tasks with a knowledge-seeking focus. For example, the two participants who completed the quantitative physiology lessons had the opportunity to use an interactive tool to increase their knowledge of concepts. Extended use of the interactive tool might align with the self-directed knowledge-seeking aspects of lifelong learning. Although there is no data related to how the students used the interactive tool, timing data indicates that K.F. looked at the simulation tool for 41 seconds and R.F. looked at the tool for only seven seconds.

The manner in which a participant engaged with the interactive aspects of the physiology and biofluids lessons may be indicative of self-motivated, continual learning. These would include the highlighted words linked to the glossary, the videos and supplemental physiology text material, and the research articles that were accessible in the resource library. Students who view these non-required elements of online learning may value continual, self-directed learning. Y.S. and S.A. had the most glossary views with 50 and 10, respectively. K.F. viewed three videos and S.A. viewed two videos that were embedded in the physiology lessons. R.F. and S.A. did not view any of these videos. Although K.F. made extensive use of the biofluids resource library, he did not view any of the supplemental physiology text. S.A. viewed two of the supplementary physiology texts and six of the articles in the resource library. Although R.F. mentioned that the resource library was valuable, he only viewed two biofluids articles and did not access any of the physiology texts. Finally, Y.S. only viewed one of the physiology texts and none of the research articles on biofluids topics.

Attitudes toward self-directed learning are projected in the following responses to an interview question related to effective learning settings:

> *"[The professor] made it more enjoyable. He kept my attention which I noticed is a big thing for me… If a professor is excited about what they are talking about I'm more keen to listen in where as obviously if they are monotone, it's boring and dull. And, then I find that I have to relearn the material all by myself, which is a lot more difficult, but then it almost seems to me that going to the lecture is pointless if they can't retain my attention."[Y.S.]*
>
> *"It helps a lot if you have friends in your classes because then you can ask them for help. I'd say that's usually what I do the most. Then just sort of working with others to complete things and making sure that it's not just them doing it for you – that they really help you understand it. And then if you can help other people understand it, I think that helps too because that just reinforces things in your head."* [R.F.]
>
> *"I would learn [by taking more of] an initiative. If you didn't understand a concept, go to office hours. And the big key was that the professor had to understand where you were coming from, so it was really a matter of talking to them and getting to know them. Then when they start to figure out where your strengths are, what you're coming from, then they could help you understand a problem."* [K.F.]
>
> *"I took a semester of Spanish, but I wasn't going anywhere with it. But, it's not that the class didn't prepare me; it's just that I didn't continue with it. I'm not sure if there's really any class that I never got anything out of. I think that I got something out of all of my classes, whether it's friends or networking or just kind of learning how to study for that type of a class. It's not necessarily knowledge or content.* [S.A.]

7.4.6.5 Metacognition

Adaptive experts demonstrate high degrees of metacognition with their ability to monitor their own knowledge level. Individuals with high metacognitive abilities possess knowledge about when and how to use particular strategies for learning or for problem solving (Metcalfe & Shimamura, 1994). Attempting the review questions multiple times may indicate a participant is aware of their own knowledge level and wants to improve their understanding of the concepts.

Even more so than multiple quiz attempts, multiple lesson attempts can indicate a learner's perceived need to review or relearn content material to increase knowledge level. Similarly, when a participant views an article in the resource library on more than one occasion it may show that they perceive gaps in their knowledge that can be filled by reviewing the article. All four participants had repeated lessons and quizzes. R.F. and K.F. had repeated views of articles in the resource library.

Learning objective views can be reflective of setting the stage to know what one needs to learn to achieve an adequate knowledge level. All of the participants viewed the learning objectives for at least one lesson. Y.S. and K.F. viewed learning objectives for three lessons while R.F. viewed the objectives for nine of the eleven lessons.

In the brainstorming phase of the challenge learning model, students begin to organize their thoughts about the presented problem. It is interesting to note that during her team's brainstorming meeting, S.A. expresses a desire to put an outline of developing ideas in place as the group was wrapping up the meeting:

> *"Ok so I guess what we have so far is oxygen is toxic at high pressures, no one has ever dove that deep before, can explore breathing a gaseous mixture other than air (to avoid oxygen toxicity and nitrogen narcosis, oxygen has a hard time traveling out into tissues at high pressures, and blood flow slows at high pressures. Right? Should I just put that all on the wiki?"* [S.A.]

All of the participants were able to easily talk about their strategies for learning during the interviews. The following are some specific quotes related to metacognitive behaviors and strategies:

> *"I try to go to the book and go over what the teacher has taught and try to find patterns within – especially in chemistry with reactions, you can find patterns – but it is difficult."* [Y.S.]

> *"I like it a lot when before a test or something, they give you the objectives. So, they'll tell you this is what you need to know broadly. Then, I'll look through those, and if I think to myself that I have no clue what they're talking about or something, then I know that I need to look back and strengthen that."* [R.F.]

> *"Initially I take the material like it's a piece of theoretical research. So, I'll absorb anything you can and make sure you understand the details so you can apply the detail to any scenario, then I'll try to think about how it really comes into play in real-world applications, where some numbers may not be used, where some are, where you need certain decimal places, where you don't. Then, it's really nice to understand like what is in theory."* [K.F.]

> *"Well, I'll be honest with you. I do have a little bit of a tendency to take charge, so I do try to keep it in the back of my mind the whole time that the other people are just as smart as I am, and they're just as capable…[The] one thing that I found is the best way to navigate that is instead of being "this is what I think we should do," pose everything as kind of a suggestion and get other people's input. To really make sure and listen to what your members are saying, and kind of be sure everyone has a part of it."* [S.A.]

7.4.5 Validity and reliability (trustworthiness)

The validity and reliability of qualitative data analysis relies on the concept of trustworthiness. Four criteria have been considered presenting trustworthiness of the analysis: credibility, transferability, dependability, and confirmability (Lincoln & Guba, 1985). In this study, to increase credibility, the coding process and how data have been associated with themes of adaptive expertise have been detailed. Additionally, the interview data were used to support the interpretations of the learning record from the preliminary study. This created a cross-check between the qualitative analysis of the learning records and the participants' own descriptions of their views of learning. The case analyses incorporate thick description and the data are detailed so that judgments can effectively be made about the transferability of the research to other contexts. The details of the analysis process are reported to demonstrate the consistency and dependability of the process.

7.5 Discussion

Using a case study comparison, this study explores the extent to which the AdEX Index predicts the presence and level of five theoretical components of adaptive expertise: knowledge efficiency, innovation, flexibility, lifelong learning skills and metacognition. Since adaptive expertise develops over time, it is not surprising that all of the undergraduate students in the study demonstrated some level of adaptive expertise. Also, as expected, none of the undergraduate students were adaptive experts in any particular subject or discipline.

We observed activities that may align with theoretical components of adaptive expertise in undergraduate learning. The study participants with higher AEP scores appear to have more learning behaviors that align with three of the theoretical components: innovation, lifelong learning skills, and metacognition. However, there is insufficient evidence to draw conclusions.

7.6 Summary, Implications and Future work

Although not a test of the validity of the Index of Adaptive Expertise, we present a qualitative analysis of the theoretical components of the construct and their alignment with scores on the metric. As in many engineering disciplines, the undergraduate curriculum cannot teach everything a student will need to know in future courses or when they begin their career. It can, however, focus on helping students to develop adaptive expertise. Valid and reliable assessment tools can provide instructors with the feedback they need to help their students attain a higher level of the components of the adaptive expertise construct.

As research continues on adaptive expertise in engineering and other disciplines, future work should consider which, if any, of the theoretical components most influence adaptive expertise. Additionally, validity and reliability testing of existing measures of adaptive expertise is warranted.

Chapter 8 - Conclusions and considerations for future research

As stated in Chapter One, one of the purposes of this dissertation was to address whether undergraduate engineering students were better prepared to learn advanced topics in biomedical engineering if they learned physiology via a quantitative, concept-based approach rather than a qualitative, system-based approach? To specifically evaluate this question, three experimental hypotheses were proposed:

> H_{o1}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a quantitative approach and those who were taught via a qualitative approach.
>
> H_{o2}: There is no difference in levels of adaptive expertise between those who were taught prerequisite physiology concepts via a system-based approach and those who were taught via a concept-based approach.
>
> H_{o3}: There is no difference in levels of adaptive expertise based on an interaction between mathematical approach and the way that the course content is structured.

Through the processes of designing a mixed-methods research study to test these hypotheses, conducting a human subjects experiment with undergraduate engineering students, and evaluating the resultant quantitative and qualitative data, several contributions have been made to the field of biomedical engineering education. This dissertation highlights three contributions: a curriculum contribution, an applied pedagogical contribution and a theory-testing contribution.

8.1 Creating a concept-based physiology curriculum

The curriculum contribution focuses on the physiology sub-curriculum of undergraduate biomedical engineering programs. Teaching physiology using a concept-based taxonomy has been suggested as an effective alternate approach for all physiology students. Biomedical engineering students, however, may particularly benefit from this type of curriculum. Several different taxonomies have been suggested in the literature (Michael & McFarland, 2011; Modell, 2000; Silverthorn, 2002) but few have reported on using these taxonomies to change curriculum or courses. Using the taxonomy proposed by the VaNTH ERC specifically for physiology courses in the biomedical engineering curriculum (Silverthorn, 2002), this dissertation describes a process by which physiology courses structured around organ systems could be converted to courses that focus on core physiology concepts. Although the VaNTH taxonomy is used in the example, the process can be used with any concept-based taxonomy.

Introductory physiology courses that use concept-based approaches may better allow students to make connections between engineering principles and the human body. In order to validate that assumption, engineering students need to have access to courses that focus on concepts. The detailed example of how a course could be changed from one that follows the system-based standard to one structured around concepts may promote the development of more concept-based courses to allow engineering students the opportunity to learn physiology in this manner.

8.2 Facilitating collaborative problem-solving in online learning environments

An applied pedagogical or teaching contribution is made through the description of spaces used for collaborative problem-solving. Three different online communication tools and the associated instructor facilitation were used to create the online collaborative spaces described in this study: an online discussion forum, avatar-based chat in a multi-user virtual environment, and a wiki. Online forums were not used by students even when they could be used to directly contact a subject-matter expert. In the avatar-based chat environment, an instructor or teaching assistant using an avatar played the role of a peer facilitator to schedule and start the meetings. Finally, the observations of student use of the wiki revealed that students were more likely to engage in cooperative writing as opposed to collaborative writing. Undergraduate students may need additional training on how to use these collaborative spaces more effectively.

8.3 Using multiple case study comparison to analyze adaptive expertise

A theory-testing contribution is made through the case study comparisons between participants with high and low scores on the Index of Adaptive Expertise (AdEX Index). The AdEX Index has been used to calculate a weighted effect of adaptive expertise that considers factual knowledge, conceptual knowledge and transfer. Although the metric has been used in several engineering studies, no validity or reliability data has been reported.

To begin to test the validity of the AdEX Index, this case study comparison between high and low scoring participants considered five theoretical components of adaptive expertise: knowledge efficiency, innovation, flexibility, lifelong learning skills and metacognition. The learning performance data, observations of online learning, survey responses and interview data were used to provide a description of the two high-scoring participants and the two low-scoring participants. After presenting a within-case description of each participant, between-case comparisons were made. There was not sufficient data upon which to draw conclusions.

8.4 Recommendations for future research

The quantitative analysis of the effect of mathematical approach and content structure on adaptive expertise showed no significant findings. The power and effect size statistical analyses of the study indicated that the design would require prohibitively large sample sizes. Future research activities should target specific elements of adaptive expertise (i.e. flexibility, innovation, lifelong learning, metacognition and knowledge) by determining dependent measures with larger effect sizes. Additionally, researchers might explore the validity of the Index of Adaptive Expertise as a measure of the presence of the theoretical elements of the adaptive expertise construction.

As the number of undergraduate engineering courses offered online or in a hybrid manner increases, it is important to identify best practices. Further research should explore how best to create learning environments in which students can collaborate on engineering challenges and design problems. Additionally, assessment tools must be created and validated to provide instructors with tools to measure and promote the development of adaptive expertise.

8.5 Summary

Although the effect size of Adaptive Expertise in Physiology was too small to be quantitatively tested using the experiment designed for this study, the mixed methods research approach used yielded interesting data about adaptive expertise in undergraduate engineering students.

We could not refute the hypothesis that concept-based physiology curriculum has no effect on adaptive expertise in engineering students. For that hypothesis to be tested, a different research design would be needed. It is hoped that by describing the development of the concept-based lessons used in this study, physiology educators who instruct biomedical engineering students will consider restructuring all or part of their system-based courses or lessons.

The online course delivery component of this research provided interesting data on how students used online learning materials both collaboratively and individually. As more engineering courses are developed as online and hybrid courses, the findings of this study may contribute to best practices for the development and facilitation of online collaboration activities.

Finally, the ability to track how students engage with online learning materials provided the opportunity to analyze learning for evidence of adaptive expertise. Using the theoretical elements of the adaptive expertise construct proposed in the current body of literature, case studies were used to compare study participants with high scores on an Index of Adaptive Expertise to those with low scores. Although there was not sufficient evidence upon which to determine how the Index of Adaptive Expertise predicts innovation, lifelong learning skills, and metacognition than knowledge efficiency and flexibility, the case studies described in this dissertation show student learning activities and behaviors that could be reinforced as students navigate the undergraduate engineering curriculum and develop the adaptive expertise that will make them effective engineers.

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Appendix A: Taxonomy – Systems Physiology Domain (VaNTH, 2007b)

I. Cells, Tissues and Organs
- A. Studying Cells and Tissues
- B. Cellular Anatomy
  1. Cell Membrane
  2. Cytoplasm
  3. Nonmembranous Organelles
  4. Membranous Organelles
  5. The Nucleus
- C. Tissues of the Body
  1. Extracellular Matrix
  2. Cell Junctions
  3. Epithelia
  4. Connective Tissue
  5. Muscle and Nerve
- D. Organs

II. Cellular Metabolism
  1. Energy in Biological Systems
  2. Energy and Work
  3. Kinetic and Potential Energy
  4. Transformation of Energy
  5. Thermodynamics
- B. Chemical Reactions
  1. Energy Transfer During Reactions
- C. Enzymes
  1. The Activation Energy of Reactions
  2. Enzyme-Substrate Binding
  3. Factors Affecting Enzyme Activity
  4. Cofactors and Coenzymes
  5. Factors Affecting Reaction Rate
  6. Types of Enzymatic Reactions
- D. Metabolism
  1. Regulation of Metabolic Pathways
  2. ATP Energy and Transfer
- E. ATP Production
  1. Glycolysis
  2. Anaerobic Metabolism
  3. Aerobic Metabolism
  4. The Electron Transport System
  5. ATP Production by Mitochondria
  6. Energy Yield of Glucose

7. Conversion of Large Biomolecules to ATP

F. Synthetic Pathways
1. Glycogen Synthesis
2. Glucose Synthesis
3. Lipid Synthesis
4. Protein Synthesis

III. Membrane Dynamics

A. Cell Membranes
1. The Fluid Mosaic Model
2. Membrane Lipids
3. Structure of Membrane Proteins
4. Functions of Membrane Proteins
5. Membrane Carbohydrates

B. Body Fluid Compartments

C. Movement Across Membranes
1. Passive Transport: Diffusion
2. Diffusion through the Phospholipid Bilayer
3. Mediated Transport by Membrane Proteins
4. Facilitated Diffusion
5. Active Transport
6. Vesicular Transport Across Membranes
7. Movement of Molecules Across Epithelia

D. Distribution of Water and Solutes in the Body
1. Osmotic, Chemical and Electrical Equilibria
2. Water Distributes throughout the Body
3. Osmosis and Osmolarity
4. Tonicity of Solutions
5. Resting Membrane Potential

IV. Communication, Integration, and Homeostasis

A. Cell to Cell Communication
1. Gap Junctions
2. Paracrines and Autocrines
3. Long-Distance Communication
4. Cytokines

B. Receptors and Signal Transduction
1. Receptors
2. First Messengers
3. Signal Transduction Pathways

C. Homeostasis
1. The Development of the Concept of Homeostasis
2. Homeostasis and Disease

D. Control Pathways: Response and Feedback Loops
1. Local and Reflex Control Pathways
2. Response Loops

3. Feedback Loops
4. Feedforward Control
5. Biological Rhythms
6. Comparison of Nervous, Endocrine and Neuroendocrine Reflexes

V. Introduction to the Endocrine System
- A. Hormones
  1. The Discovery of Hormones
  2. What makes a chemical a Hormone
- B. Classification of Hormones
  1. Peptide Hormones
  2. Steroid Hormones
  3. Amine Hormones
- C. Control of Hormone Release
  1. Trophic Hormones
  2. Negative Feedback in Endocrine Reflexes
  3. Endocrine Reflexes
  4. Hormone Interactions
- D. Endocrine Pathologies
  1. Hypersecretion
  2. Hyposecretion
  3. Abnormal Tissue Responsiveness
  4. Diagnosis of Endocrine Pathologies
- E. Hormone Evolution

VI. The Nervous System
- A. Organization of the Nervous System
- B. Cells of the Nervous System
  1. Neurons
  2. Glial Cells
- C. Electrical Signals in Neurons
  1. Changes in Membrane Potential
  2. Role of Ions in Electrical Signals
  3. Gated Ion Channels
  4. Graded Potentials
  5. Summation of Graded Potentials
  6. Action Potentials
  7. Refractory Period
  8. Coding for Stimulus Intensity
  9. The Na+/K+ Pump
  10. Conduction of Action Potentials
  11. Factors Influencing the Speed of Conduction
  12. Chemical Factors Affecting Electrical Activity
- D. Cell-to-Cell Communication in the Nervous System
  1. The Synapse
  2. Neurotransmitters

3. Calcium and Neurotransmitter Release
4. Postsynaptic Responses
5. Two-way Communication at Synapses
6. Disorders of Synaptic Transmission
7. Development of the Nervous System
8. Responses of Neurons to Injury

VII. The Central Nervous System
- A. Evolution of Nervous Systems
- B. Anatomy of the Central Nervous System
  1. Protection of the Central Nervous System
  2. Blood Supply to the Brain
  3. Gray Matter and White Matter
- C. The Spinal Cord
- D. The Brain
  1. Brain Stem
  2. Cerebellum
  3. Diencephalon
  4. Cerebrum
- E. Brain Function
  1. Neurotransmitters and Neuromodulators in the central nervous system
  2. States of Arousal and the Reticular Formation
  3. The Hypothalamus and Homeostasis
  4. Emotion and Motivation
  5. Learning and Memory
  6. Language
  7. Personality and Individuality

VIII. Sensory Physiology
- A. General Properties of Sensory Systems
  1. Receptors
  2. Sensory Pathways
  3. Sensory Transduction
  4. Stimulus Coding and Processing
- B. Somatic Senses
  1. Pathways for Somatic Perception
- C. Chemoreceptoin: Smell and Taste
  1. Olfaction
  2. Taste
- D. The Ear: Hearing
  1. Sound Waves
  2. Transduction of Sound
  3. The Middle Ear
  4. The Cochlea of the Inner Ear
  5. Sound Transduction through the Cochlea
  6. Sound Discrimination

7. Auditory Pathways
8. Hearing Loss

E. The Ear: Equilibrium
1. Anatomy of the Vestibular Apparatus
2. Function of the Vestibular Apparatus
3. Equilibrium Pathways

F. The Eye and Vision
1. Anatomy of the Eye and Optic Tract
2. Optics: Focusing Light on the Retina
3. Phototransduction and the Retina
4. Signal Processing in the Retina
5. Visual Processing in the Central Nervous System

IX. Efferent Peripheral Nervous System: The Autonomic and Somatic Motor Divisions

A. The Autonomic Division
1. The Adrenal Medulla
2. Autonomic Neurotransmitters
3. Autonomic Neurotransmitter Receptors
4. Interaction of the Sympathetic and Parasympathetic Branches
5. Control of the Autonomic Division
6. Disorders of the Autonomic Nervous System

B. The Somatic Motor Division
1. Anatomy of the Somatic Division
2. The Neuromuscular Junction

X. Muscle

A. Skeletal Muscle
1. Skeletal Muscle Fibers
2. Skeletal Muscle Contraction
3. Regulation of Contraction: Troponin and Tropomyosin
4. Excitation – Contraction Coupling
5. Skeletal Muscle Metabolism
6. Muscle Fatigue
7. Types of Skeletal Muscle Fibers
8. Tension and Fiber Length
9. Summation of Twitches
10. The Motor Unit
11. Contraction in Intact Muscles

B. Mechanics of Body Movement
1. Isotonic and Isometric Contractions
2. Bones, Joints, Levers, and Fulcrums
3. Muscle Disorders

C. Smooth Muscle
1. Smooth Muscle Fibers
2. Variable Force in Smooth Muscle Cells
3. Smooth Muscle Contraction

4. Membrane Potentials
5. Calcium and Smooth Muscle Contraction
6. Chemical Control of Smooth Muscle Contraction

D. Cardiac Muscle

XI. Control of Body Movement

A. Nervous Reflexes
1. Nervous Reflex Pathways
2. Modulation of Neuronal Activity

B. Autonomic reflexes

C. Skeletal Muscle Reflexes
1. Muscle Spindles
2. Golgi Tendon Organs
3. Myotatic Reflexes and the Crossed Extensor Reflex

D. The Integrated Control of Body Movement
1. Types of Movement
2. Integration of Movement within the Central Nervous System

E. Control of Movement in Visceral Muscles

XII. Cardiovascular Physiology

A. Overview of the Cardiovascular System
1. Functions of the Cardiovascular System
2. Anatomy of the Cardiovascular System

B. Pressure, Volume, Flow, and Resistance
1. Pressure
2. Pressure and Volume
3. Pressure and Flow
4. Resistance and Flow
5. Flow Rate and Velocity of Flow

C. Cardiac Muscle and the Heart
1. Structure of the Heart
2. Properties of Cardiac Muscle Cells
3. Excitation – Contraction Coupling in Cardiac Muscles
4. Action Potentials in Myocardial Cells

D. The Heart as a Pump
1. Electrical Conduction in the Heart
2. Pacemakers and Heart Rate
3. The Electrocardiogram
4. Cardiac Cycle
5. Pressure-Volume Curves
6. Stroke Volume
7. Cardiac Output
8. Homeostatic Control of Heart Rate
9. Control of Stroke Volume

XIII. Blood Flow and the Control of Blood Pressure

A. The Blood Vessels
   1. Vascular Smooth Muscle
   2. Arteries and Arterioles
   3. Capillaries
   4. Venules and Veins
   5. Angiogenesis
B. Blood Pressure
   1. Blood Pressure in the Systemic Circulation
   2. Arterial Blood Pressure
   3. Estimation of Blood Pressure
   4. Factors Influencing Mean Arterial Pressure
   5. Blood Volume and Blood Pressure
C. Resistance in the Arterioles
   1. Myogenic Autoregulation
   2. Local Control of Vascular Smooth Muscle
   3. Reflex Control of Vascular Smooth Muscle
D. Distribution of Blood to the Tissues
E. Exchange at the Capillaries
   1. Velocity of Blood Flow
   2. Capillary Exchange
   3. Capillary Filtration and Reabsorption
F. The Lymphatic System
   1. Edema: Disruption of Capillary Exchange
G. Regulation of Blood Pressure
   1. The Baroreceptor Reflex
   2. Orthostatic Hypotension
H. Cardiovascular Disease
   1. Risk Factors
   2. Hypertension

XIV. Blood
A. Plasma and the Cellular Elements of Blood
   1. Plasma
   2. The Cellular Elements
   3. Blood Cell Production
B. General Pattern of Blood Cell Production
   1. The Control of Hematopoiesis: Cytokines, Growth Factors and Interleukins
   2. Colony-Stimulating Factors and Leukopoiesis
   3. Thrombopoietin and Platelet Production
   4. Erythropoietin and Red Blood Cell Production
C. Red Blood Cells
   1. Red Blood Cell Structure
   2. Hemoglobin Synthesis nad Metabolism
   3. The Life Cycle of a Red Blood Cell
   4. Disorders of Red Blood Cells
D. Platelets and Coagulation

1. Platelets
2. Hemostasis
3. Platelet Aggregation
4. Coagulation
5. Anticoagulants

XV. Respiratory Physiology
- A. The Respiratory System
  1. The Thorax
  2. The Lungs
  3. The Airways of the Conducting System
  4. The Alveoli and Gas Exchange
  5. Pulmonary Circulation
- B. Gas Laws
  1. Partial Pressure of Gases
  2. Gas Flow
  3. Pressure-Volume Relationship of Gases
  4. Solubility of Gases in Liquids
- C. Ventilation
  1. The Conditioning of Inspired Air
  2. Pressure Changes during Ventilation
  3. Inspiration
  4. Expiration
  5. Intrapleural Pressure
  6. Lung Compliance
  7. Surfactant
  8. Resistance of the Airways to Air Flow
  9. Pulmonary Function Tests
  10. Efficiency of Breathing
  11. Gas Composition of the Alveoli
  12. Matching Ventilation to Alveolar Blood Flow
- D. Gas Exchange in Tissues
- E. Gas Transport in Blood
  1. Oxygen Transport
  2. Hemoglobin
  3. The Oxygen-Hemoglobin Dissociation Curve
  4. Factors Affecting Oxygen-Hemoglobin Binding
  5. Carbon Dioxide Transport
- F. Regulation of Ventilation
  1. Neurons in the Medulla Control Breathing
  2. Chemical Control of Ventilation
  3. Mechanoreceptor Reflexes
  4. Higher Brain Control

XVI. Kidneys
- A. Functions of the Kidneys

B. Anatomy of the Urinary System
    1. Gross Anatomy
    2. The Nephron
C. Processes of the kidneys
    1. Filtration, Reabsorption, Secretion, and Excretion
    2. Volume and Osmolarity Changes in the Nephron
D. Filtration
    1. Anatomy of the Renal Corpuscle
    2. Filtration
    3. Glomerular Filtration Rate
    4. Regulation of GFR
E. Reabsorption
    1. Transepithelial Transport
    2. Saturation of Renal Transport
F. Secretion
    1. Conpetition and Penicillin Secretion
G. Excretion
    1. Using Clearance to Determine Renal Handling of a Substrate
H. Micturitoin

XVII. Fluid and Electrolyte Balance
A. Homeostasis of Volume and Osmolarity
B. Water Balance and the Regulation of Urine Concentration
    1. Overview of Water Balance
    2. The Role of Kidneys in Water Balance
    3. Receptors for Water Balance Reflexes
    4. The Importance of Osmolarity
    5. Urine concentration
    6. Loop of Henle: A Countercurrent Multiplier
    7. Antidiuretic Hormone
C. Sodium Balance and the Regulation of Extracellular Fluid Volume
    1. Sodium Balance and Aldosterone
    2. Control of Aldosterone Secretion
    3. Angiotensin II
    4. Atrial Natriuretic Peptide
D. Potassium Balance
E. Behavioral Mechanisms in Salt and Water Balance
    1. Thirst
    2. Salt Appetite
    3. Avoidance Behaviors
F. Integrated Control of Volume and Osmolarity
    1. Disturbances of Salt and Water Balance
    2. Homeostatic Response to Dehydration
G. Acid-Base Balance
    1. Why pH is regulated
    2. Sources of Acids and Bases in the Body

3. Buffer Systems in the Body
4. Respiratory Compensation in Acid-Base Disturbances
5. Renal Compensation in Acid-Base Disturbances
6. Disturbances of Acid-Base Balance

XVIII. Digestion

A. Function and Processes of the Digestive System

B. Anatomy of the Digestive System

1. Gross Anatomy
2. Histology of the Gastrointestinal Tract

C. Motility

1. Gastrointestinal Smooth Muscle
2. Patterns of Contraction
3. Movements of Food through the Gastrointestinal Tract

D. Secretion

1. Secretion of Digestive Enzymes
2. Secretion of Mucus
3. Fluid and Electrolyte Secretion

E. Digestion and Absorption

1. Overview of Digestion
2. Overview of Absorption
3. Carbohydrates
4. Proteins
5. Fats
6. Nucleic Acids
7. Vitamins and Minerals
8. Water and Electrolytes
9. Digestion and Absorption in the Large Intestine

F. Regulation of GI Function

1. The Enteric Nervous System
2. Digestive Hormones
3. Pracrines in the GI Tract

G. Integration of GI Function: The Stomach

1. Secretions in the Stomach
2. Events Following Ingestion of a Meal

XIX. Endocrine Control of Metabolism

A. Energy Balance and metabolism

1. Energy balance
2. Temperature Regulation
3. Measurement of Energy Balance and Metabolism
4. Fed and Fasted States
5. The Regulation of Metabolic Pathways
6. Metabolism in the Fed State
7. Metabolism in the Fasted State

B. Endocrine Control of Metabolism: Pancreatic Hormones

1. The Endocrine Pancreas
2. Dual Regulation of Metabolism by Insulin and Glucagon
3. Insulin
4. Glucagon

C. Neurally Mediated Aspects of Metabolism
1. The Adrenal Glands
2. Thyroid Hormones

D. Endocrine Control of Growth
1. Growth Hormone
2. Tissue Growth
3. Bone Growth
4. Calcium Balance

XX. The Immune System

A. Pathogens of the Human Body
1. Bacteria and Viruses
2. Life Cycle of a Virus

B. Immune Response

C. Anatomy of the Immune System
1. Lymphoid Tissues of the Body
2. Cells of the Immune System

D. Innate Immunity
1. Physical and Chemical Barriers
2. Phagocytes
3. The Inflammatory Response

E. Acquired Immunity
1. Lymphocyte Life Cycle
2. B Lymphocytes
3. Antibodies
4. T Lymphocytes
5. Natural Killer Lymphocytes

F. Immune Response Pathways
1. Response to Bacterial Invasion
2. Response to Viral Infections
3. Allergic Responses
4. Recognition of Foreign Tissue
5. Recognition of Self
6. Immune Surveillance

G. Integration between the Immune, Nervous and Endocrine Systems
1. Stress and the Immune System

XXI. Exercise

A. Metabolism and Exercise
1. Role of Hormones
2. Oxygen Consumption
3. Factors Limiting Exercise

B. Ventilatory Responses to Exercise
C. Cardiovascular Responses to Exercise
1. Cardiac Output
2. Peripheral Blood Flow
3. Blood Pressure
4. The Baroreceptor Reflex
D. Feedforward Responses to Exercise
E. Temperature Regulation
F. Exercise and Health
1. Exercise and Cardiovascular Disease
2. Exercise and Diabetes Mellitus
3. Exercise, Stress and the Immune System

XXII. Reproduction and Development
A. Sex Determination
1. The Sex Chromosomes
2. Sexual Differentiation in the Embryo
B. Basic Patterns of Reproduction
1. Gametogenesis
2. Hormonal Control of Reproduction
C. Male Reproduction
1. The Testes and Sperm Production
2. Hormonal Control of Spermatogenesis
3. Male Accessory Glands
4. Other Effects of Androgen
D. Female Reproduction
1. Female Reproductive Anatomy
2. The Ovary
3. The Menstrual Cycle
4. Other Effects of Estrogen
E. Procreation
1. The Human Sexual Response
2. Erection and Ejaculation
3. Contraception
4. Infertility
F. Pregnancy and Parturition
1. Fertilization
2. Implantation and Development
3. Hormones of Pregnancy
4. Labor and Delivery
5. Lactation
G. Growth and Aging
1. Puberty

XXIII. Menopause and Aging

Appendix B: ABET Accredited Programs Summary

2012 Review of Physiology courses of ABET-Accredited BME Programs **Data collected June 2012**

ABET-accredited BME programs	73	
Required Standalone Physiology course(s)	Offered by BME Department	42
	Offered by Life Science Department	24
	One by BME/One by Biology	3
	No required course	4
Required credits in Physiology course(s)	No credits	4
	3 credits	16
	4 credits	18
	5 credits	1
	6 credits	11
	7 credits	4
	8 credits	15
	9 credits	2
	12 credits	2
Recommended semester for 1st course in physiology	1st semester	2
	2nd semester	0
	3rd semester	15
	4th semester	33
	5th semester	2
	6th semester	4
	7th semester	6
	8th semester	0
	no required course	4
	info not available	1
Recommended semester for last course in physiology	1st semester	0
	2nd semester	0
	3rd semester	3
	4th semester	16
	5th semester	19
	6th semester	24
	7th semester	6
	8th semester	0
	no required course	4
	info not available	1

Required physiology and mathematics courses data collected for 73ABET-accredited BME undergraduate programs (June 2012)

University
Degree Offered
Required Physiology Course(s)
Recommended Matriculation semester
Department offering physiology course(s)
Required Mathematics Course(s) [Recommended Matriculation semester]

Arizona State University
BS, Bioengineering
Special Topics: Anatomy & Physiology: Cell Tissues Physiology (4)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [5th semester]

Boston University
BS, Biomedical Engineering
Systems Physiology (4)
5th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

Brown University
BS, Biomedical Engineering
Principles of Physiology (3)
n/a
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]

Bucknell University
BS, Biomedical Engineering
Human Physiology (3)
6th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Case Western Reserve University
BS, Biomedical Engineering
Physiology – Biophysics I (3)
3rd semester
Physiology – Biophysics II (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

City University of New York, City College
BE, Biomedical Engineering
Physiological Processes (3)
5th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [5th semester]

Columbia University
BS, Biomedical Engineering
Quantitative Physiology I (4)
5th semester
Quantitative Physiology II (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [4th semester]

Drexel University
BS, Biomedical Engineering
Human Physiology I (4)
4th semester
Human Physiology II (4)
5th semester
Bioscience & Biotechnology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Linear Algebra [4th semester]

Duke University
BSE, Biomedical Engineering
Quantitative Physiology (3)
3rd semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [5th semester]
Linear Algebra [4th semester]

Florida Gulf Coast University
BS, Bioengineering
Human Physiology Engineers I (3)
5th semester
Human Physiology Engineers II(3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Florida International University
BS, Biomedical Engineering
Engineering Analysis of Biological Systems I (3)
5th semester
Engineering Analysis of Biological Systems II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Georgia Institute of Technology
BS, Biomedical Engineering
Systems Physiology I (4)
5th semester
Systems Physiology II (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Illinois Institute of Technology
BS, Biomedical Engineering
Animal Physiology (3)
7th semester
Biology
Animal Physiology Lab (1)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [4th semester]
Differential Equations [3rd semester]

Indiana University-Purdue University Indianapolis
BS, Biomedical Engineering
Quantitative Physiology (3)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Lawrence Technological University
BS, Biomedical Engineering
Anatomy & Physiology and Lab (4)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Lehigh University
BS, Bioengineering
Bioengineering Physiology (4)
4th semester
Bioengineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Advanced Engineering Math [5th semester]

Louisiana Tech University
BS, Biomedical Engineering
Human Anatomy & Physiology I (3)
3rd semester
Human Anatomy & Physiology II (3)
4th semester
Animal Physiology Lab (1)
5th semester
Biological Sciences
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Marquette University
BS, Biomedical Engineering
Systems Physiology (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [5th semester]

Michigan Technological University
BS, Biomedical Engineering
Anatomy/Physiology I (3)
3rd semester
Anatomy/Physiology II (3)
4th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [4th semester]

Milwaukee School of Engineering
BS, Biomedical Engineering
Physiology I (3)
5th semester
Physiology II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [3rd semester]

New Jersey Institute of Technology
BS, Biomedical Engineering
Introduction to Human Physiology I (2)
1st semester
Introduction to Human Physiology II (1)
2nd semester
Engineering Models in Physiology I((3)
5th semester
Engineering Models in Physiology II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

North Carolina State University at Raleigh
BS, Biomedical Engineering
Human Physiology for Engineers I (3)
5th semester
Human Physiology for Engineers II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Northwestern University
BS, Biomedical Engineering
Systems Physiology I (2.67)
7th trimester
Systems Physiology II (2.67)
8th trimester
Systems Physiology III (2.67)
9th trimester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [2nd semester]

Oregon State University
BS, Bioengineering
Anatomy & Physiology I (3)
3rd semester
Anatomy & Physiology II (3)
4th semester
Zoology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [2nd semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

Penn State
BS, Bioengineering
Physiology / Physiology Lab (4)
3rd semester
Biology
Analysis of Physiological Systems/ Physiological Simulation (4)
5th semester
Bioengineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [4th semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

Purdue University
BS, Biomedical Engineering
Physiology for Engineers (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Rensselaer Polytechnic Institute
BS, Biomedical Engineering
Human Physiological Systems (4)
5th semester
Biology
Advanced Systems Physiology (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]

Rose-Hulman Institute of Technology
BS, Biomedical Engineering
Physiology Systems I (4)
5th semester
Physiology Systems II (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [1st semester]
Calculus III (Multivariable) [2nd semester]
Differential Equations [3rd semester]

Rutgers University
BS, Biomedical Engineering
BME System Physiology (3)
5th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Saint Louis University
BS, Biomedical Engineering
Human Physiology (3)
3rd semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

State University of New York – Binghamton
BS, Bioengineering
No required physiology course
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [5th semester]

Stevens Institute of Technology
BS, Biomedical Engineering
Engineering Physiology (4)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]
Calculus III (Multivariable) [5th semester]

Stony Brook University
BE, Biomedical Engineering
No required physiology course
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

Syracuse University
BS, Bio-Engineering
Engineering Analysis of Living Systems I (4)
5th semester
Engineering Analysis of Living Systems I (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Texas A&M
BS, Biomedical Engineering
Physiology for Bioengineers I (4)
3rd semester
Physiology for Bioengineers II (4)
4th semester
Veterinary Physiology and Pharmacology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

The Catholic University of America
BS, Biomedical Engineering
Physiology (4)
6th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

The George Washington University
BS, Biomedical Engineering
Principles and Practices of Biomedical Engineering (4)
5th semester
Electrical and Computer Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Advanced Engineering Math [6th semester]

The Johns Hopkins University
BS, Biomedical Engineering
Systems Bioengineering I: Cells and Cardiovascular System (4)
3rd semester
Systems Bioengineering II: Neural Systems (4)
4th semester
Systems Bioengineering III: Genes to Cells (4)
5th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [4th semester]
Differential Equations [2nd semester]
Linear Algebra [3rd semester]

The University of Akron
BS, Biomedical Engineering
Anatomy & Physiology I & Lab (4)
3rd semester
Anatomy & Physiology II & Lab (4)
4th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

The University of Memphis
BS, Biomedical Engineering
Vertebrate Physiology (4)
5th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

The University of Toledo
BS, Bioengineering
Physiology for Bioengineers (3)
5th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

Tulane University
BS, Biomedical Engineering
Anatomy and Physiology I and Lab (4)
5th semester
Quantitative Physiology and Lab (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Alabama at Birmingham
BS, Biomedical Engineering
Mammalian Physiology (4)
5th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

University of California-Irvine
BS, Biomedical Engineering
Quantitative Physiology: Sensory Motor Systems (4)
7th trimester
Quantitative Physiology: Organ Transport Systems (4)
8th trimester
Biomedical Engineering
Calculus I (Single Variable) [1st and 2nd trimesters]
Calculus II (Multivariable) [3rd and 6th trimesters]
Differential Equations [5th trimester]
Linear Algebra [4th trimester]

University of California-San Diego
BS, Bioengineering
Bioengineering Physiology I (4)
5th semester
Bioengineering Physiology II (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [4th semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

University of Central Oklahoma
BS, Biomedical Engineering
Human Physiology & Lab (4)
5th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Cincinnati
BS, Biomedical Engineering
Anatomy and Physiology I (4)
1st semester
Anatomy & Physiology II (4)
2nd semester
Anatomy & Physiology III (4)
3rd semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [5th semester]

University of Connecticut
BS, Biomedical Engineering
Physiological Modeling (3)
3rd semester
Human Physiology and Anatomy (4)
5th semester
Physiology and Neurobiology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Hartford
BS, Biomedical Engineering
Anatomy and Physiology I (4)
5th semester
Anatomy and Physiology II (4)
6th semester
Biology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [6th semester]
Advanced Engineering Math [7th semester]

University of Illinois at Chicago
BS, Bioengineering
No required physiology course
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Iowa
BSE, Biomedical Engineering
Human Physiology (3)
4th semester
Integrative Physiology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]
Linear Algebra [2nd semester]

University of Louisville
BBE, Bioengineering
Human Physiology (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

University of Maryland College Park
BS, Bioengineering
Modeling Physiological Systems and Lab (4)
5th semester
Bioengineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Miami
BSBE, Biomedical Engineering
Medical Systems Physiology (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]

University of Michigan
BSE, Biomedical Engineering
Quantitative Physiology (4)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Minnesota – Twin Cities
BBmE, Biomedical Engineering
Principles of Human Physiology (6)
5th semester
Physical and Biological Sciences (for BME)
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

University of Pennsylvania
BS, Bioengineering
Vertebrate Physiology **or** Engineering Principles of Human Physiology (3)
5th semester
Biology **or** Bioengineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]

University of Pittsburgh
BS, Bioengineering
Human Physiology (3)
5th semester
Biological Sciences
Dynamic Systems: A Physiological Perspective (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

University of Rochester
BS, Biomedical Engineering
Quantitative Physiology (4)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [4th semester]
Differential Equations [3rd semester]

University of Southern California
BS, Biomedical Engineering
Physiological Systems (3)
7th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Mathematics of Physics and Engineering [4th semester]

University of Tennessee of Knoxville
BSBME, Biomedical Engineering
Engineering Physiology (3)
5th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [4th semester]

University of Texas at Austin
BS, Biomedical Engineering
Engineering Physiology I (4)
5th semester
Engineering Physiology II (4)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]

University of Utah
BS, Bioengineering
Physiology for Engineers (4)
5th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations/Linear Algebra [3rd semester]

University of Virginia
BS, Biomedical Engineering
Physiology I (3)
3rd semester
Physiology II (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Differential Equations [3rd semester]

University of Washington
BS, Bioengineering
Failure Analysis of Human Physiology with Lab (4)
9th trimester
Biomedical Engineering
Calculus I (Single Variable) [1st trimester]
Calculus II [2nd trimester]
Calculus III (Multivariable) [3rd trimester]
Differential Equations [5th trimester]
Linear Algebra [6th trimester]

University of Wisconsin-Madison
BS, Biomedical Engineering
Physiology with Lab (5)
5th semester
Physiology
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III [3rd semester]
Differential Equations [3rd semester]

Vanderbilt University
BS, Biomedical Engineering
Systems Physiology I (3)
5th semester
Systems Physiology II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III (Multivariable) [3rd semester]
Differential Equations [4th semester]
Linear Algebra [4th semester]

Virginia Commonwealth University
BS, Biomedical Engineering
Quantitative Physiology I (4)
3rd semester
Quantitative Physiology II (4)
4th semester
School of Medicine: Physiology
Calculus II (Single Variable) [1st semester]
Calculus III (Multivariable) [2nd semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

Washington State University
BS, Biomedical Engineering
No required physiology course
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III [3rd semester]
Differential Equations [4th semester]
Linear Algebra [3rd semester]

Washington University
BS, Biomedical Engineering
Quantitative Physiology I (4)
5th semester
Quantitative Physiology II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III [2nd semester]
Differential Equations [3rd semester]
Linear Algebra [4th semester]

Western New England College
BS, Biomedical Engineering
Engineering Physiology I (3)
5th semester
Engineering Physiology II (3)
6th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III [4th semester]
Differential Equations [3rd semester]

Worcester Polytechnic Institute
BS, Biomedical Engineering
Physiology and Engineering (3)
4th semester
Biomedical Engineering
Calculus I (Single Variable) [1st semester]
Calculus II [2nd semester]
Calculus III [3rd semester]
Differential Equations [4th semester]
Linear Algebra [4th semester]

Wright State University
BS, Biomedical Engineering
Anatomy and Physiology I (4.5)
3rd semester
Anatomy and Physiology I (4.5)
4th semester
Biology
Calculus I (Single Variable) [2nd semester]
Calculus II [3rd semester]
Calculus III [4th semester]
Differential Equations [5th semester]
Linear Algebra [5th semester]

Appendix C: Concepts and subtopics for physiology lessons

Lesson	Concept	Subtopic
Lesson 1: Form	Levels of organization in the body	Cell theory Four basic tissue types Organs and list of organ systems
	Compartmentation	Cell membrane Heart structure and anatomy Plasma Blood-brain barrier, Blood-CSF barrier
Lesson 2: Function	Structure/function relationships	Structure and function of tissue types Pulmonary and systemic circuits Major vessel anatomy of head and neck
	Molecular interactions	Formed elements Viscosity Functions of blood Gas transport in blood Gas law: Henry Gas exchange at lungs and tissues
	Biological energy	Metabolic requirements of the brain Cerebral blood flow
Lesson 3: Physical Properties	Mechanics: movement and associated forces	The heart as a pump
	Elastic properties	Arteries, Arterioles, Veins, Venules Cardiac muscle cells and tissue
	Bioelectricity	Events of a heartbeat
	Emergent properties of complex systems	
Lesson 4: Variables and Measurement	Biological units of measure	
	Physiological variables	Formed elements Hematocrit Cardiac cycle Cardiac output, Stroke volume
	Scaling in biological systems	
Lesson 5: Information Processing	Biological transduction (molecular/sensory)	Baroreceptors Chemoreceptors
	Communication and coordination	CNS Structural overview Neural tissue Cerebrospinal fluid The events of a heartbeat Capillaries Metarterioles, Anastomoses
Lesson 6: Control Systems	Homeostasis/dynamics and control systems	Cellular homeostasis Baroreceptors

		Chemoreceptors
	Mass flow (transport)	Membrane transport Diffusion, Filtration Facilitated diffusion, Active transport Carrier-mediated transport Gas law: Fick Alveoli Bulk flow Blood flow Pulmonary circulation(flow of blood and air) Capillary exchange
	Mass balance	Starling forces and net filtration pressure
	Heat balance	
Lesson 7: Pressure/ Flow/ Resistance	Pressure – flow – resistance	Blood pressure, Mean arterial pressure Cardiac output Respiratory system structures Lung structure and anatomy Gas laws: Dalton and Boyle Pulmonary circulation(flow of blood and air)

Appendix D: Physiology Pre/Post Assessment

QUESTION 1:

Learning Objective: Student will recognize homeostasis as a main point of cell theory
Bloom Taxonomy Level: Knowledge

PRE-TEST

Which of the following statement(s) is/are TRUE about the process of monitoring the internal environment of the human body and making necessary corrections for maintenance of adequate levels?

[A] The process occurs at the cellular level
[B] The process is called homeostasis
[C] The process is an example of a state of equilibrium
[D] A and B
[E] A and C

POST-TEST

Which of the following statement(s) is/are TRUE about homeostasis?

[A] The process only occurs at the molecular level
[B] The process monitors the internal environment of the human body
[C] The process is an example of a state of equilibrium
[D] A and B

QUESTION 2:

Learning Objective: Student will illustrate how structure and function of body tissues are related
Bloom Taxonomy Level: Application

PRE-TEST

In the space below, give one example of how the structure and function of epithelial tissue are related

POST-TEST

In the space below, give one example of how the structure and function of connective tissue are related

QUESTION 3:

Learning Objective: Student will identify a normal hematocrit value for a healthy adult male
Level: Knowledge

PRE-TEST

A 20 year old male is in the emergency room. When his blood is tested, the hematocrit level is 52%. Is this physiological variable within the normal range?

[A] Yes
[B] No

POST-TEST

A 20 year old male is in the emergency room. When his blood is tested, the hematocrit level is 32%. Is this physiological variable within the normal range?

[A] Yes
[B] No

QUESTION 4:

Learning Objective: Student will cite examples of the function of blood
Bloom Taxonomy Level: Comprehension

PRE-TEST

In the space below, give examples of the function of blood in the human body.

POST-TEST

In the space below, give examples of the function of blood in the human body.

QUESTION 5:

Learning Objective: Students will differentiate blood vessels based on their elasticity
Bloom Taxonomy Level: Analysis

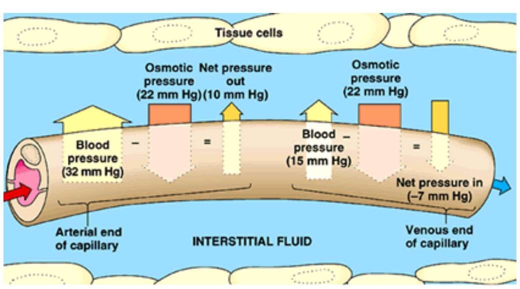
PRE-TEST

Which of the following types of blood vessel contains the most elastic tissue?
- [A] Arterioles
- [B] Veins
- [C] Capillaries
- **[D] Arteries**

POST-TEST
Which of the following types of blood vessel contains the most elastic tissue?
- [A] Arterioles
- [B] Veins
- [C] Capillaries
- **[D] Arteries**

QUESTION 6:

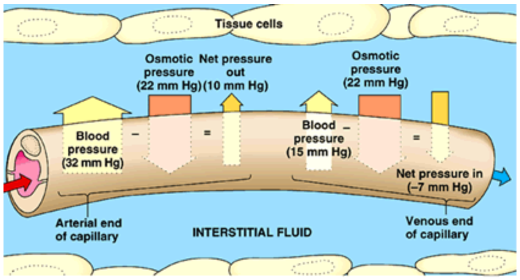
Learning Objective: Student will assess effects of capillary filtration given changes in typical pressures
Bloom Taxonomy Level: Evaluation



PRE-TEST
Fluid filtration through the capillary endothelium is dependent on the balance between hydrostatic and osmotic pressures of the capillary and interstitial fluid. Typically, there is a mean net driving force outwards from the capillary as a whole with a 10 mm Hg outward pressure at the arterial end of the capillary and 7 mm Hg inward pressure at the venous end of the capillary?

What would happen at the venous end of the capillary if the osmotic pressure was double the normal value?

POST-TEST



Fluid filtration through the capillary endothelium is dependent on the balance between hydrostatic and osmotic pressures of the capillary and interstitial fluid. Typically, there is a mean net driving force outwards from the capillary as a whole with a 10 mm Hg outward pressure at the arterial end of the capillary and 7 mm Hg inward pressure at the venous end of the capillary?

What would happen at the arterial end of the capillary if the osmotic pressure was double the normal value?

QUESTION 7:

Learning Objective: Student will summarize function of blood-brain barrier
Bloom Taxonomy Level: Comprehension

PRE-TEST

Which of the following statements about the blood-brain barrier is FALSE?

[A] It does not allow simple (non-facilitated) diffusion of water-soluble molecules
[B] It is a physical barrier containing endothelial cells
[C] It is selectively permeable
[D] It contains neurons and glial cells

POST-TEST

Which of the following statements about the blood-brain barrier is TRUE?

[A] It allows simple (non-facilitated) diffusion of small lipid-soluble molecules
[B] It is a physical barrier containing smooth muscle cells
[C] It allows simple (non-facilitated) diffusion of water-soluble molecules
[D] It contains neurons and glial cells

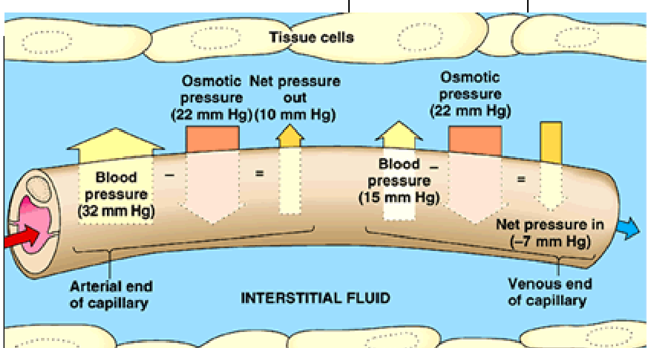
Appendix E: Physiology Assessment Rubrics

Physiology Pre-test Question 2 (4 points)	**1**	**1**	**2**
Student will illustrate how structure and function of body tissues are related In the space below, give on example of how the structure and function of epithelial tissue are related.	Correctly states **structure** of epithelial tissue: cells are closely adhered together and attached to underlying connective tissue by a basement membrane	Correctly states **function** of epithelial tissue: provide strength and a barrier to restrict movement of proteins and other large molecules from the connective tissue into the epithelium	States one example of how structure and function are **related (1)** Example uses the structure and function terms in the rubric**. (1)**

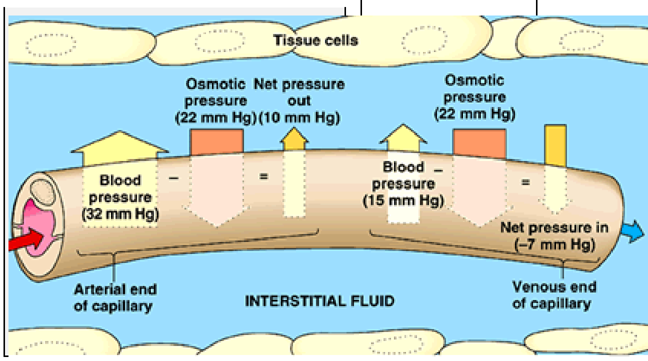
Physiology Post-test Question 2 (4 points)	**1**	**1**	**1**
Student will illustrate how structure and function of body tissues are related In the space below, give on example of how the structure and function of connective tissue are related.	Correctly states **structure** of connective tissue: diverse, catchall category; all have specialized cells, protein fiber, and a fluid known as ground substance; highly vascular with receptors	Correctly states **function** of connective tissue: provide structure and support to the body; conduit for nutrients; protection; transport of materials; storage of energy reserves; defense of the body	States one example of how structure and function are **related (1)** Example uses the structure and function terms in the rubric. **(1)**

Physiology Pre-test/Post-test Question 4 (5 points)	**1**	**1**	**1**	**1**	**1**
Student will give examples of the function of blood	Transport nutrients and wastes (Oxygen and Carbon Dioxide)	Communication via transport of hormones	Maintain body temperature	Maintain pH Level	Defense against toxins and pathogens
In the space below, give examples of the function of blood in the human body.					

Physiology Pretest Question 6 (4 points)	**1**	**1**	**1**	**1**
Student will assess effects of capillary filtration given changes in typical pressures				
Fluid filtration through the capillary endothelium is dependent on a balance between hydrostatic and osmotic pressures of the capillary and interstitial fluid. Typically, there is a mean net driving force outwards from the capillary as a whole with a 10 mm Hg outward pressure at the arterial end of the capillary and a 7 mm Hg inward pressure at the venous end of the capillary. What would happen at the venous end of the capillary if the osmotic pressure was double the normal value.	Recognizes that there would be a net pressure of 29 mm Hg at venous end of capillary	Recognizes that the net pressure would be in the direction forcing fluid into the capillary (absorption)	Recognize that this extra fluid will be pulled into the plasma	State at least one result of the extra fluid in the plasma



Physiology Post-test Question 6 (4 points)	**1**	**1**	**1**	**1**
Student will assess effects of capillary filtration given changes in typical pressures				
Fluid filtration through the capillary endothelium is dependent on a balance between hydrostatic and osmotic pressures of the capillary and interstitial fluid. Typically, there is a mean net driving force outwards from the capillary as a whole with a 10 mm Hg outward pressure at the arterial end of the capillary and a 7 mm Hg inward pressure at the venous end of the capillary. What would happen at the arterial end of the capillary if the osmotic pressure was double the normal value.	Recognizes that there would be a net pressure of 12 mm Hg at arterial end of capillary	Recognizes that the net pressure would be in the direction forcing fluid into the capillary (absorption)	Recognize that this would cause the substances in the blood to not enter the interstitial fluid and cells.	State at least one result of the blood components not leaving the capillary.



Appendix F: Biofluids Pre/Post Assessment

QUESTION 1:
Learning Objective: Student will define hydrostatic pressure
Bloom Taxonomy Level: Knowledge

PRE-TEST

Hydrostatic pressure is the pressure exerted by a fluid [**at equilibrium**, in motion] due to the force of [the fluid, **gravity**].

POST-TEST

Hydrostatic pressure is measured with fluid [**at rest**, in motion]. The pressure will [**increase**, decrease] as depth of a fluid column increases.

QUESTION 2:
Learning Objective: Student will use hydrostatic pressure equation to make predictions
Bloom Taxonomy Level: Application

PRE-TEST

A 7-ft basketball center is called into the game after sitting on the bench and resting for five minutes. Imagine that pressure transducers have been put in place to measure blood pressure. The two pressure transducers are placed on the carotid artery; one is just above the aortic arch and the other is just below the ear.

When the player is sitting on the bench, you would expect the transducer at the ear to show a [higher, **lower**, equivalent] pressure than the pressure measured at the aortic arch.

When the player stands to enter the game, you would expect the transducer at ear level to show a [higher, **lower**, equivalent] than the pressure at the aortic arch.

POST-TEST

The blood pressures measured at the front paw of 2 dogs (a Great Dane and a Chihuahua) are compared to the blood pressure at each dog's heart.

Given that the aortic pressure is the same for each dog, what can be expected concerning the measurement at the foot under normal conditions? The blood pressure at the paw will be [lower for the Great Dane, **higher for the Great Dane**, the same for both dogs] when they are standing. The blood pressure at the paw will be [lower for the Great Dane, higher for the Great Dane, **the same for both dogs**] when they are lying prone with their feet approximately at heart level?

QUESTION 3:

Learning Objective: Student will identify allometric relationships
Bloom Taxonomy Level: Comprehension

PRE-TEST

When a physiological trait has a higher rate of change than the rate of change of the organism's body mass, it is an example of a [**positive**, negative] [isometric, **allometric**] relationship.

POST-TEST

What type of relationship is found when a physiological trait has a lower rate of change than the rate of change of the organism's body mass?

A. positive isometric
B. negative isometric
C. **negative allometric**
D. positive allometric

QUESTION 4:

Learning Objective: Student will apply dimensional analysis rules to a given problem
Bloom Taxonomy Level: Application

PRE-TEST

The pressure drop (Δp) for flow in a tube depends on density (ρ), average velocity ($\bar{v}$), tube diameter (D), tube length (ℓ), fluid viscosity (μ), and average roughness (ε).

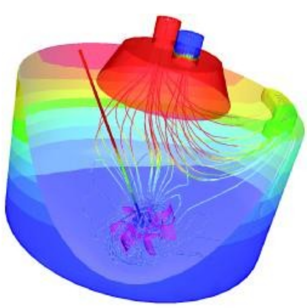
$$\Delta p = f(\rho, \bar{v}, D, \ell, \mu, \varepsilon)$$

How many physical quantities are in the stated problem? [**7**]

How many fundamental dimensions should be selected? [**3**]
How many dimensionless groups will result? [**4**]

List the fundamental dimensions you would select for this example? [**M,L,T**]

POST-TEST



The power required by an agitator in a tank is a function of density of fluid (ρ), diameter of agitator (D), fluid viscosity (μ), and number of rotations of the impeller per unit time (N).

$$P = f(\rho, D, \mu, N)$$

How many physical quantities are in the stated problem? [**5**]

How many fundamental dimensions should be selected? [**3**]
How many dimensionless groups will result? [**2**]

List the fundamental dimensions you would select for this example? [**M,L,T**]

QUESTION 5:

Learning Objective: Student will define transmural pressure
Bloom Taxonomy Level: Knowledge

PRE-TEST

In the space below, define transmural pressure as it relates to a blood vessel.

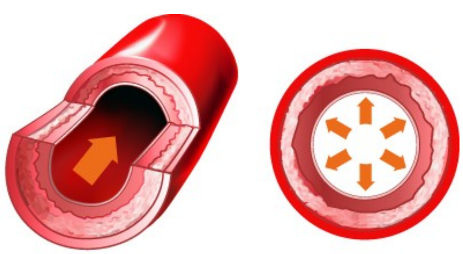
POST-TEST

In the space below, define transmural pressure as it relates to a blood vessel.

QUESTION 6:

Learning Objective: Student will interpret Laplace's Law related to blood vessels
Bloom Taxonomy Level: Comprehension

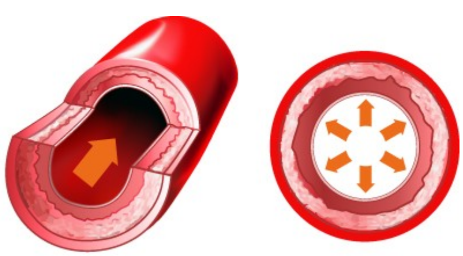
PRE-TEST



According to Laplace's Law, as the diameter of a blood vessel increases, the tension in the vessel walls ______.

A. **increases**
B. decreases
C. increases then decreases
D. remains the same
E. none of these is correct

POST-TEST



According to Laplace's Law, as the thickness of the blood vessel wall increases, the tension in the vessel wall ______.

A. increases
B. increases then immediately decreases
C. decreases
D. remains the same
E. none of these is correct

QUESTION 7:

Learning Objective: Student will use Poiseuille’s Law to estimate change in flow
Bloom Taxonomy Level: Application

PRE-TEST

Poiseuille's equation is often used to provide estimations related to biofluid flow. By this law, estimate the effect on flow rate when the vessel radius decreases by half.

Choose one answer.

A. Flow rate decreases to 1/4 the original flow.
B. Flow rate decreases to 1/16 the original flow.
C. Flow rate decreases to 1/2 the original flow.
D. Flow rate doubles
E. Flow rate increases to four times the original flow

POST-TEST

Poiseuille's equation is often used to provide estimations related to biofluid flow. By this law, estimate the effect on flow rate when the vessel length decreases fourfold.

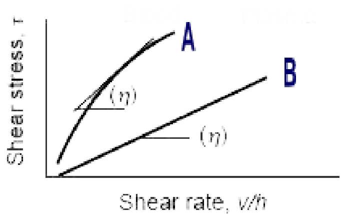
Choose one answer.

A. Flow rate decreases to 1/4 the original flow
B. Flow rate decreases to 1/16 the original flow
C. Flow rate decreases to 1/2 the original flow.
D. Flow rate doubles
E. Flow rate increases to four times the original flow

QUESTION 8:

Learning Objective: Student will use Poiseuille’s Law to estimate change in flow
Bloom Taxonomy Level: Application

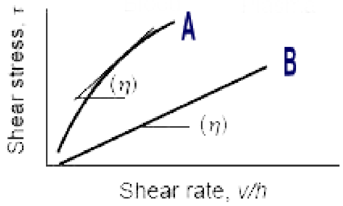
PRE-TEST



The slope of the relation between shear stress and shear rate of a fluid (represented by η) is the __________. [**viscosity**]

Which slope best represents the relationship between shear stress and shear rate for blood plasma? [A,**B**]

POST-TEST



The slope of the relation between shear stress and shear rate of a fluid (represented by η) is the ___________. [**viscosity**]

Which slope best represents the relationship between shear stress and shear rate for blood? [**A**,B]

Appendix G: Biofluids Assessment Rubrics

BIOFLUIDS PRE/POST QUESTION 5	1	1
Describe transmural pressure and its relationship to absolute pressure	Recognizes that it is a pressure difference	Recognizes that the difference is between the pressure inside the vessel wall and the pressure outside the vessel wall
In the space below, define transmural pressure as it relates to a blood vessel.		

Appendix H: Beta Testing IRB Protocol

University of Wisconsin-Madison **Application for Initial Review of Research Projects Involving Human Subjects** **Education Research IRB**	**For Office Use Only** **Protocol #: SE-2008-0297** **Date Received: 5/8/2008**

General Protocol Information and Personnel Information

General Protocol Information

Current Protocol Title
Evaluating the Design of Online Learning Modules in Physiology and Biofluids

Current Principal Investigator
Naomi C Chesler, Biomedical Engineering

Expected Project Starting Date (mm/dd/yyyy):
9/1/2008

Expected Project Duration:
2 years

If this research is part of a previously approved project or is related to another project, please provide the other protocol number(s) and approval date(s):

Please select the type of review you are requesting:

- (•) Application for Initial Review
- ( ) Application for Protocol Development Activities Only

Personnel Information

Conflict of Interest Questions

Is this a clinical research project?

○ Yes ◉ No

Do any project personnel receive incentives for recruiting human participants or for any other purpose directly related to the study?

○ Yes ◉ No

Do any personnel involved in the design, conduct, or analysis of the study have any proprietary interests (royalties, patents, trademarks, copyrights, or licensing agreements) involving any agent, device, or software being evaluated as part of the study?

○ Yes ◉ No

In addition to the sponsor(s) of this project, are other companies or business entities:
a) involved in or potentially affected by this research project OR
b) owners or licensee of technologies being tested by this research project?

○ Yes ◉ No

If yes, please list the names of those companies/business entities.

HIPAA Health Care Component

Are you in the HIPAA Health Care Component of the University or within the Affiliated Covered Entity AND are you using Protected Health Information (individually identifiable health information)? If yes, you will be asked to submit a HIPAA Authorization Form. In most cases, this form can be combined with the cosent form. Templates can be found on the HIPAA Privacy Rule Research Guidance webpage.

○ Yes ◉ No

Are you outside of the HIPAA Health Care Component but are using Protected Health Information (individually identifiable health information) from a HIPAA Covered Entity?

○ Yes ◉ No

If yes to either of the HIPAA questions, you are required to take the HIPAA Research Training Module*. You will not be able to submit your protocol until the training is completed. Any questions about HIPAA Training should be directed to the* UW-Madison HIPAA Privacy Officer.

Human Subjects Protection Training
All researchers on this protocol must complete Human Subjects Protection Training.

NOTE: Please allow 24 hours after completion of the training before attempting to submit the protocol. Information within IRB WebKit ,on who has completed the human subject training, is updated nightly.

Are any of the researchers (including key personnel) below from another institution?

Yes No

If yes, they may take UW's online tutorial, Human Subjects Protection Training, *OR their institution's training certification must be submitted to the IRB prior to submission of the protocol. The IRB will then update the system with the training date so that you may submit the protocol.*

Study Personnel

Project Personnel

Dr. Naomi C. Chesler, Ph.D. Biomedical Engineering 1550 Engineering Dr 2146 ECB	Principal Investigator chesler@engr.wisc.edu 608-265-8920
Regina K. Nelson Biomedical Engineering 1550 Engineering Dr 2145 ECB	Point of Contact reginanelson@wisc.edu 608-345-5863
Regina K. Nelson Biomedical Engineering 1550 Engineering Drive Madison WI 53706	Co-Investigator reginanelson@wisc.edu 608-345-5863

Project Sponsorhip Information (current or planned)

1) Is the research to be funded with federal funds, or are federal funds being applied for?

Yes No

If yes, what is the status of this federal proposal?

If yes, please upload the grant proposal on the Documents tab and, if required, submit two copies of the grant proposal to the appropriate IRB office.

2) Is the research to be funded by a private or non-federal sponsor? *(This includes University of Wisconsin and the State of Wisconsin)*

Yes No

3) If there is no grant or contract to fund this research, how will this research be funded?
Personal Funds

Sponsor Information

For each current or potential funding source, provide:
a. The name of the sponsoring agency (including UW funding)
b. The UW proposal number
c. The UW grant fund and account number (i.e. 144-abxx)
d. The agency award number

Sponsor	Proposal #	Fund Acct #	Agency Award #

Review Type and Questionnaire

Review Type

Request for a

Exempt Review

Expedited Review

Full Review

In order to receive an exemption from review by the IRB, *the research project must involve no more than minimal risk to subjects, no ethical concerns, and one or more* categories of research (45 CFR 46.101b). *If your project meets these criteria, you may apply for an exemption from IRB review. However, the final determination of whether the project is exempt resides with the committee, not the investigator.*

Questionnaire

Please answer *all* of the questions below.

---

1) Does the research involve **the collection of data** concerning:

a) Prisoners?

Yes No

b) Fetuses, neonates or pregnant women?

Yes No

c) The cognitively impaired?

Yes No

d) Participants who are institutionalized (e.g., in a mental health facility, nursing home, or halfway house)?

Yes No

---

2) Will the study elicit data about participants engaged in illegal or stigmatizing behaviors (e.g., illicit drug use, child abuse, alcoholism, or gambling)? *If so, provide an explanation in the study description.*

Yes No

---

3) Does the research involve deception of the participants by the researcher?

Yes No

*If **yes**, upload a debriefing statement explaining the deception under the Documents tab.*

---

4) Does the research involve:

a) Observations of behavior of participants under the age of 18 outside of an established educational setting?

Yes No

b) Survey or interviews of subjects under the age of 18?

Yes No

Note: If you answered YES to any part of questions 1-4, your research is subject to full review by a human subjects committee. Please check Full Review above.

---

5) Does the research involve data from participants with:

a) Learning disabilities?

Yes No

b) Emotional disabilities?

Yes No

c) Developmental disabilities?

Yes No

d) Physical disabilities?

Yes No

---

6) Does the research involve:

a) Non-UW researchers?

Yes No

If yes, they may take UW's Human Subjects Protection Training *OR their institution's training certification must be submitted to the IRB prior to submission of the protocol. The IRB will then update the system with the training date so that you may submit the protocol.*

b) Students in a classroom setting?

Yes No

c) Collection of images or audio recordings of the participants?

Yes No

d) Only the use of existing data (i.e., no human subject contact)?

Yes No

e) Participants who have a status relationship with the researchers (e.g., students or employees)?

Yes No

f) Participants who do not speak English?

Yes No

If yes, please upload the consent form or oral consent script in the participant's native language and an English translation on the Documents tab.

---

7) Will the study target or exclude a particular gender or ethnic or racial group?

Yes No

---

8) Will the research be conducted at or in conjunction with another institution that has its own institutional review board for human subjects research?

Yes No

If yes, please upload the approval (or evidence that the protocol has been submitted) to the other IRB(s) for review on the Documents tab.

---

9) Will the research be conducted outside of the United States?

○ Yes ◉ No

Study Description

Please supply the information requested below in lay terms (non-technical language). Your responses should be concise. Pay attention to your word count limit.

ABSTRACT

In lay terms using 300 words or less (approximately 2000 characters), please describe the GENERAL PURPOSE of the study and how human participants will be involved. List the SPECIFIC AIMS and HYPOTHESES or RESEARCH QUESTIONS.

This study is being conducted to evaluate the usability of online learning modules developed to see how different approaches to teaching physiology (quantitative vs. qualitative and systems-based vs. concepts-based) influence how students learn subsequent material for which physiology is a prerequisite. The learning modules are being developed to use in a follow-up study which will test the different approaches to teaching physiology. Participants in this current study will beta test the online modules. The participants will be recruited from the Fall 2008 Physiology 335 class at the University of Wisconsin-Madison. All students will be invited to participate; however we anticipate only 50-80 will choose to be involved. Participants will be asked to complete two online learning modules. One of the learning modules will focus on physiology topics. It will take 4-8 hours to complete depending on how the participant interacts with the modules. The second will introduce a topic in biofluids for which the physiology material is a prerequisite. It will take 8-12 hours to complete. The modules are segmented so that the student can work in 10-20 minute blocks of time as his/her schedule permits. All interaction with the learning modules will be Internet-based. A pre-test and post-test will be included with the online modules. Participants will also interact online with an instructor and other participants completing the same module. The specific aim of this research is to test the usability, length, and validity of the learning modules. Participants will be queried after completing the modules via an online survey, email interview and a phone interview. As participants complete the modules and provide feedback, improvements to the modules will be made and additional participants will test the re-designed modules as part of an iterative design process.

STUDY DESIGN AND METHODS

Inclusion Criteria

Outline the inclusion criteria for participants, explaining the rationale for the involvement of any special groups, e.g., prisoners, pregnant women, participants with cognitive impairments and non-English speaking participants. Explain how participants will be recruited or the sampling procedures. Describe the characteristics of the targeted participants, including gender, age ranges, ethnic background, and health/treatment status.

Students in the Fall 2008 Physiology 335 class at the University of Wisconsin-Madison will be invited to participate in this study. The class size is generally 500 students. Students enrolled in the course come from many departments, including nursing, biomedical engineering, kinesiology, occupational and physical therapy. The students are generally in their 2nd to 4th academic year, although there are some graduate students enrolled in the course. This population has been chosen because they have a general interest in the physiology and biofluids topics. All students in the class will be invited to participate, although we anticipate only a small fraction will volunteer for the study. An announcement will be made at the beginning of class during the first week of the fall semester. Although the course instructor has been contacted to seek permission to make a class announcement, he is not part of the research team and will have no access to participant data. A recruitment flyer will also be handed out that includes contact information and details on participating. All recruitment and consent tasks will be handled by doctoral student Regina Nelson. Because the development of the learning modules is iterative, changes to the modules will be made after the first participants test and provide feedback on the online modules. After the fifth week of classes, a second announcement will be made before either class or lab sessions and the flyers again handed out to students giving them another chance to participate. Students may participate in both the first and second rounds of module testing.

Number of Participants
Enter the number of participants you anticipate including from each targeted group listed above.

50-80

Justify the number of participants (sample size) entered above.

All students in the Physiology 335 class will be invited to participate in the study. Participation will require approximately 4-8 hours to complete the physiology module and 8-12 hours to complete the biofluids module. The total time need not be consecutive, as interactions with the online material can be done in segments as short as 10-15 minutes. Since participants will interact with the online modules at their most convenient times and places, the 12-20 hour timeframe should not outweigh the benefit the participant will receive learning about a topic of general interest to them since they are taking a physiology course. The class size is rather large; however, only a 10-15% response rate is anticipated.

Role of Participants

Describe the role of participants, including what they will be asked to do, for how long, where, and whether deception will occur. Explain if and how confidentiality will be maintained. If the research study involves collections of images or audio recordings of participants, explain how the material will be used, who will see the images or hear the recordings, and in what setting.

Participants will be asked to complete two online learning modules developed around physiology and biofluids topics. The physiology learning modules will cover topics in the central nervous system, cardiovascular system, and blood flow. The content of these modules will be presented in four different ways with the amount of mathematics used in the presentation varied and with the physiology content structured around the organ systems or around key concepts (i.e. homeostasis, mass flow, resistance). All of the participant's interaction with the learning modules will occur online via the Internet at either a computer lab or at the participant’s home or preferred wireless location. The physiology learning module will take between 4-8 hours to complete and the biofluids modules will take between 8-12 hours; however, the modules will be divided into segments that can be completed 10-20 minutes at a time. Participants can complete the segments at their own convenience although participants will be asked to complete each learning module within a 2-week timeframe. A pre-test and post-test will be administered online at the beginning and end of the learning module. Online interactions may also occur via email, chat or online posting in a class forum. No deception will occur. After completing the module, participants will be surveyed on their experience. The participant may also be interviewed either via email or on the phone about their experience. No images or audio recordings of the participants will be recorded. Participants will be assigned a number to use when completing the online modules. The number will be recorded on the signed consent form and filed for the duration of the study. This information will not be shared with anyone other than the PI and Co-investigator of the study.

Compensation
Describe any compensation the participants will receive, including course credit.

All participants will be entered in a drawing for a chance to win one of two iPod Nanos. Given our estimates of the number of participants, the odds of winning will be approximately 2 chances in 80 or better. The value of each iPod is approximately $200.

Sites
Describe sites where this research will take place.

All of the interaction with the modules will be completed online. Participants may choose to complete the module at any location where they have an Internet connection (i.e. home, computer lab, or anywhere with a laptop and wireless connection). To evaluate the modules, online survey and interview tools will also be used. After they have completed the online modules, the participant will be interviewed via phone about their experience.

Does the study involve participants from places other than common public spaces?

○ Yes ◉ No

*If **yes**, upload documentation of permission from the appropriate source (e.g. superintendent of schools, community center director, clinic research director) under the Documents tab.*

Measurement Procedures
Describe all measurement procedures to be used in this study.

This investigation is designed to determine the usability and validity of online learning modules. In conjunction with each of the learning modules, a pre-test and post-test will be administered. For the pre-test and post-test, the variable of interest is the construct of adaptive expertise which is measured by three components that can be quantified: factual knowledge, conceptual knowledge and transfer of learning. Although these tests are part of the learning modules, this research study is concerned with the iterative development of the learning modules (i.e. improving upon the prototype that will be presented to the first participants). The data of interest will be answers to questions related to participant interaction with the modules. These questions will be presented after the student has completed the learning modules via an online questionnaire, email interview questions, and a phone interview with the investigator. Data collected will be used to improve the online learning modules. An outline of the types of questions to be asked on the survey and interview protocol is attached. The data will be used to make adjustments to improve the learning modules. For example, if data indicates that participants think a part of a module takes too long to complete, the module will be evaluated and changes made to potentially shorten the length of time required. If the results of this beta test indicate that an assessment question is misleading, the question will be evaluated and corrections made to the modules and assessments. All data collection and data analysis will be conducted by doctoral student Regina Nelson.

Will any of the following be used as part of the study: questionnaires, measurement instruments, interview protocols, or a description of topics or an approximate script?

◉ Yes ○ No

Do copies of of these questionnaires, etc., exist in electronic format?

(•) Yes ( ) No

If yes, please upload the questionnaire on the Documents tab.
If no, please provide 14 printed copies upon submission to the IRB Office.

Recruitment Materials
Will any of the following be used as part of the study: flyers, brochures, advertisements, or other recruitment materials?

(•) Yes ( ) No

Do copies of of these recruitment materials exist in electronic format?

(•) Yes ( ) No

If yes, please upload the recruitment materials on the Documents tab.
If no, please provide 14 printed copies upon submission to the IRB Office.

RISK/BENEFIT ASSESSMENT
Participants should be protected against injury and invasion of their privacy, and their dignity should be preserved. Risks fall under the following categories: physical, psychological, social, economic, legal, and other.

Risks
Are there risks to the participants?

( ) Yes (•) No

If yes, please assess the types and level of each type of risk involved in the research.

Steps to Minimize Risks
Describe the steps that will be taken to minimize risk.

Medical or Professional Intervention
Discuss provisions for ensuring necessary medical or professional intervention in the event of adverse effects to the participants or additional resources for participants.

Alternative Treatments
If appropriate, describe alternative treatments and procedures that might be advantageous to the participants.

Possible Benefits to the Participants
Describe the possible benefits to the participants.

Participants will be given the opportunity to learn some physiology content in an online format. They will also get a chance to apply their knowledge of physiology in exploring a topic for which some physiology knowledge is prerequisite - biofluids.

Benefits to Society
Describe the possible benefits to society.

In biomedical engineering, physiology is a core topic that is taught in different ways (different mathematical approaches and different course taxonomies). These learning modules are being developed to use in a subsequent study to test if a different mathematical approach or course taxonomy leads to better learning. This current beta test study will help develop the learning modules which will be used for that experimental investigation and also used as shareable learning resources for use in physiology and engineering disciplines.

MINORS
Will minors be included as participants in this research?

○ Yes ◉ No

If yes, and the children are over the age of 11, you must upload an Assent Form under the Documents Tab.

In determining whether children are capable of assenting, the researcher must consider the age, maturity, and psychological state of the children involved in the study. Indicate how confidentiality will be maintained and attach all assent forms. Generally, written assent is required for minors over the age of eleven. The assent document should include all eight elements listed in Part VIII and be written in language appropriate for the age of the child. The research investigator is responsible for retaining all signed assent documents for at least seven years past the completion of the research activity.

ADDITIONAL INFORMATION
If you have any additional information that would be helpful to the IRB in making a determination with regards to this submission, please describe below.

Appendix I: Quantitative Study IRB Protocol

University of Wisconsin-Madison **Application for Initial Review of Research Projects Involving Human Subjects** Social and Behavioral Sciences IRB	For Office Use Only **Protocol #: SE-2008-0754** **Date Received: 12/10/2008**

General Protocol Information and Personnel Information

General Protocol Information

Current Protocol Title
Testing Approaches to Physiology Instruction for Biomedical Engineering Undergraduate Students

Current Principal Investigator
Naomi C Chesler, Biomedical Engineering

Expected Project Starting Date (mm/dd/yyyy):
2/1/2009

Expected Project Duration:
18 months

If this research is part of a previously approved project or is related to another project, please provide the other protocol number(s) and approval date(s):
SE-2008-0297 Approved 6/9/2008

Please select the type of review you are requesting:

- (●) Application for Initial Review
- ( ) Application for Protocol Development Activities Only

Personnel Information

Conflict of Interest Questions

Is this clinical research?

Yes No

Do any project personnel receive incentives for recruiting human participants or for any other purpose directly related to the study?

Yes No

Do any personnel involved in the design, conduct, or analysis of the research study, have any proprietary interests (royalties, patents, trademarks, copyrights, or licensing agreements) involving any agent, device or software being evaluated as part of the study?

Yes No

In addition to the sponsor(s) of this project, are other companies or business entities:
a) involved in or potentially affected by this research project OR
b) owners or licensee of technologies being tested by this research project?

Yes No

If yes, please list the names of those companies/business entities.

HIPAA Health Care Component

Are you in the HIPAA Health Care Component of the UW-Madison or within the Affiliated Covered Entity AND are you using Protected Health Information (individually identifiable health information)? If yes, you will be asked to submit a HIPAA Authorization Form. In most cases, this form can be combined with the consent form. Templates can be found on the HIPAA Privacy Rule Research Guidance webpage.

Yes No

Are you outside of the HIPAA Health Care Component but are using Protected Health Information (individually identifiable health information) from a HIPAA Covered Entity?

Yes No

If yes to either of the HIPAA questions, you are required to take the HIPAA Research Training Module*. You will not be able to submit your protocol until the training is completed. Any questions about HIPAA Training should be directed to the* UW-Madison HIPAA Privacy Officer.

Human Subjects Protection Training
All researchers on this protocol must complete Human Subjects Protection Training.

NOTE: Please allow 24 hours after completion of the training before attempting to submit the protocol. Information within IRB WebKit ,on who has completed the human subject training, is updated nightly.

Are any of the researchers (including key personnel) below from another institution?

○ Yes ◉ No

If yes, they may take UW's online tutorial, Human Subjects Protection Training, *OR their institution's training certification must be submitted to the IRB prior to submission of the protocol. The IRB will then update the system with the training date so that you may submit the protocol.*

Study Personnel

Use **"Other"** if a person's department or agency is not in list of Departments.

Project Personnel

Dr. Naomi C. Chesler, Ph.D. Biomedical Engineering 1550 Engineering Dr 2146 ECB	Principal Investigator chesler@engr.wisc.edu 608-265-8920
Regina K. Nelson Biomedical Engineering 1550 Engineering Dr 2145 ECB	Co-Investigator reginanelson@wisc.edu 608-345-5863

Project Sponsorship Information (current or planned)

1) Is the research to be funded with federal funds, or are federal funds being applied for?

○ Yes ◉ No

If yes, what is the status of this federal proposal?

If yes, please upload the grant proposal on the Documents tab and, if required, submit two copies of the grant proposal to the appropriate IRB office.

2) Is the research to be funded by a private or non-federal sponsor? *(This includes University of Wisconsin and the State of Wisconsin)*

○ Yes ◉ No

3) If there is no grant or contract to fund this research, how will this research be funded?
Personal funds

Sponsor Information

For each current or potential funding source, provide:
a. The name of the sponsoring agency (including UW funding)
b. The UW proposal number
c. The UW grant fund and account number (i.e. 144-abxx)
d. The agency award number

Sponsor	Proposal #	Fund Acct #	Agency Award #

Review Type and Questionnaire

Review Type

Request for a

○ Exempt Review

○ Expedited Review

◉ Full Review

In order to receive an exemption from review by the IRB, *the research project must involve no more than minimal risk to subjects, no ethical concerns, and one or more categories of research (45 CFR 46.101b). If your project meets these criteria, you may apply for an exemption from IRB review. However, the final determination of whether the project is exempt resides with the committee, not the investigator.*

Questionnaire

Please answer *all* of the questions below.

---

1) Does the research involve **the collection of data** concerning:

a) Prisoners?

○ Yes ◉ No

b) Fetuses, neonates or pregnant women?

○ Yes ◉ No

c) The cognitively impaired?

○ Yes ● No

d) Participants who are institutionalized (e.g., in a mental health facility, nursing home, or halfway house)?

○ Yes ● No

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2) Will the study elicit data about participants engaged in illegal or stigmatizing behaviors (e.g., illicit drug use, child abuse, alcoholism, or gambling)? *If so, provide an explanation in the study description.*

○ Yes ● No

---

3) Does the research involve deception of the participants by the researcher?

○ Yes ● No

*If **yes**, upload a debriefing statement explaining the deception under the Documents tab.*

---

4) Does the research involve:

a) Observations of behavior of participants under the age of 18 outside of an established educational setting?

○ Yes ● No

b) Survey or interviews of subjects under the age of 18?

○ Yes ● No

Note: If you answered YES to any part of questions 1-4, your research is subject to full review by a human subjects committee. Please check Full Review above.

---

5) Does the research involve data from participants with:

a) Learning disabilities?

○ Yes ● No

b) Emotional disabilities?

○ Yes ● No

c) Developmental disabilities?

Yes No

d) Physical disabilities?

Yes No

---

6) Does the research involve:

a) Non-UW researchers?

Yes No

If yes, they may take UW's Human Subjects Protection Training *OR their institution's training certification must be submitted to the IRB prior to submission of the protocol. The IRB will then update the system with the training date so that you may submit the protocol.*

b) Students in a classroom setting?

Yes No

c) Collection of images or audio recordings of the participants?

Yes No

d) Only the use of existing data (i.e., no human subject contact)?

Yes No

e) Participants who have a status relationship with the researchers (e.g., students or employees)?

Yes No

f) Participants who do not speak English?

Yes No

If yes, please upload the consent form or oral consent script in the participant's native language and an English translation on the Documents tab.

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7) Will the study target or exclude a particular gender or ethnic or racial group?

Yes No

---

8) Will the research be conducted at or in conjunction with another institution that has its own institutional review board for human subjects research?

Yes No

If yes, please upload the approval (or evidence that the protocol has been submitted) to the other IRB(s) for review on the Documents tab.

---

9) Will the research be conducted outside of the United States?

○ Yes ◉ No

Study Description

Please supply the information requested below in lay terms (non-technical language). Your responses should be concise. Pay attention to your word count limit.

ABSTRACT

In lay terms using 300 words or less (approximately 2000 characters), please describe the GENERAL PURPOSE of the study and how human participants will be involved. List the SPECIFIC AIMS and HYPOTHESES or RESEARCH QUESTIONS.

This study is being conducted to evaluate the effect of different approaches to teaching physiology (quantitative vs. qualitative and systems-based vs. concepts-based) on how engineering students learn subsequent material for which physiology is a prerequisite. Participants for this study will be recruited from a population of students in the College of Engineering at the University of Wisconsin-Madison who have not taken a college-level Physiology class, but have completed at least two semesters of college-level calculus. Forty-eight participants will be recruited and randomly assigned to one of four experimental conditions. All participants will be asked to complete two online learning modules. One of the learning modules will be the experimental physiology instruction condition which will provide the prerequisite content for the second module that focuses on a topic in biofluids. Depending on how intently the participant interacts with these two modules, it could take 8-16 hours to complete the study. The learning modules are segmented so that the participant can work in 10-20 minute blocks of time as his/her schedule permits. All interaction with the learning modules will be Internet-based. A pre-test and post-test will be used with the modules. Quantitative and qualitative data will also be collected as the students interact with the Internet-based modules and participate in online discussions. By collecting this data, we hope to learn how different physiology instruction methods affect how engineering students learn a biomedical engineering topic that requires background physiology knowledge.

STUDY DESIGN AND METHODS

Inclusion Criteria

Outline the inclusion criteria for participants, explaining the rationale for the involvement of any special groups, e.g., prisoners, pregnant women, participants with cognitive impairments and non-English speaking participants. Explain how participants will be recruited or the sampling procedures. Describe the characteristics of the targeted participants, including gender, age ranges, ethnic background, and health/treatment status.

Students in the College of Engineering at the University of Wisconsin-Madison who have not yet taken a college-level physiology course, but have taken at least two semesters of college-level calculus will be invited to participate in this study. Recruitment flyers will be distributed in buildings housing the College of Engineering. Announcements will be made in College of Engineering newsletters. All recruitment and consent tasks will be handled by doctoral student Regina Nelson.

Number of Participants
Enter the number of participants you anticipate including from each targeted group listed above.

48

Justify the number of participants (sample size) entered above.

Forty-eight participants will allow twelve participants per experimental condition. A preliminary power analysis was conducted using a standard deviation of 0.25 which follows with tests of educational interventions and an effect size of 0.50 which is moderate. The preliminary analysis was done without considering the covariate (pre-test). With the four cells of a 2x2 factorial design, the power analysis was done considering 32 participants thus allowing 8 per cell. With the within-cell standard deviation of 0.25, this design achieved 78% power when an F test was used to test mathematical approach, content structure, and the mathematical approach/content structure interaction at a 5% significance level. Forty-eight participants, allowing 12 per cell, would increase the power of the design and also allow for attrition.

Role of Participants
Describe the role of participants, including what they will be asked to do, for how long, where, and whether deception will occur. Explain if and how confidentiality will be maintained. If the research study involves collections of images or audio recordings of participants, explain how the material will be used, who will see the images or hear the recordings, and in what setting.

Participants will be asked to complete two online learning modules developed around physiology and biofluids topics. The physiology learning modules will cover topics in the central nervous system, cardiovascular system, and blood flow. The content of these modules will be presented in four different ways with the amount of mathematics used in the presentation varied and with the physiology content structured around the organ systems or around key concepts (i.e. homeostasis, mass flow, resistance). All of the participant's interaction with the learning modules will occur online via the Internet at either a computer lab or at the participant's home or preferred wireless location. Completing the two learning module will take between 8-16 hours, depending on how intently the individual interacts with the module; however, the modules will be divided into segments that can be completed 10-20 minutes at a time. Participants can complete the segments at their own convenience although participants will be asked to complete the modules within a 4-week timeframe. A pre-test and post-test will be administered online at the beginning and end of both learning modules. Online interactions will also occur via email, virtual chat or posting in a class discussion forum. No deception will occur. There will be an electronic record of the participant's interaction with the online learning. There will be no audio recordings of the participant, nor images of the participant; however, in a virtual environment, the text of an online discussion will be recorded and an image of the avatar selected by the participant may be recorded.

Compensation
Describe any compensation the participants will receive, including course credit.

All participants will be entered in a drawing with a chance to win one of two iPod Nanos. The odds of winning will be approximately 2 chances in 48. The value of each iPod is approximately $175.

Sites
Describe sites where this research will take place.

All of the interaction with the modules will be completely online. Participants may choose to complete the module at any location where they have an Internet connection (i.e. home, computer lab, or anywhere with a laptop and wireless access). Online discussions in a virtual environment will also occur.

Does the study involve participants from places other than common public spaces?

Yes No

*If **yes**, upload documentation of permission from the appropriate source (e.g. superintendent of schools, community center director, clinic research director) under the Documents tab.*

Measurement Procedures

Describe all measurement procedures to be used in this study.

A pre-test and post-test assessment will be administered to participants in association with the physiology training learning module. This will be in the form of an online quiz and will be specifically related to the content of the physiology module. It will assess the degreet to which the participant mastered the content presented.

When the participants are working through the biofluids module, the focus will shift to their adaptive expertise in physiology. Adaptive expertise in physiology is the variable of interest. Adaptive expertise will be measured as a composite of the factual knowledge, conceptual knowledge and knowledge transfer of physiology content presented in the study. Quantitative and qualitative data will be collected using several assessment devices. These will include online short-answer assessments, evaluation of contributions to an online forum related to the challenge, and evaluation of participation in a guided discussion with a facilitator and two other participants working on the same challenge question. Additionally, data will be collected on how the participant maneuvers through the online learning module and which of the available resources are used in completing the module.

Will any of the following be used as part of the study: questionnaires, measurement instruments, interview protocols, or a description of topics or an approximate script?

If yes, please upload the questionnaire or other measures in on the Documents tab.

Yes No

Do copies of of these questionnaires, etc., exist in electronic format?

Yes *No*

If yes, please upload the questionnaire on the Documents tab.

Recruitment Materials

Will any of the following be used as part of the study: flyers, brochures, advertisements, or other recruitment materials?

If yes, please upload the recruitment materials on the Documents tab.

Yes *No*

Do copies of of these recruitment materials exist in electronic format?

Yes *No*

If yes, please upload the recruitment materials on the Documents tab.

RISK/BENEFIT ASSESSMENT
Participants should be protected against injury and invasion of their privacy, and their dignity should be preserved. Risks fall under the following categories: physical, psychological, social, economic, legal, and other.

Risks
Are there risks to the participants?

○ *Yes* ◉ No

If yes, please assess the types and level of each type of risk involved in the research.

Steps to Minimize Risks
Describe the steps that will be taken to minimize risk.

Medical or Professional Intervention
Discuss provisions for ensuring necessary medical or professional intervention in the event of adverse effects to the participants or additional resources for participants.

Alternative Treatments
If appropriate, describe alternative treatments and procedures that might be advantageous to the participants.

Possible Benefits to the Participants
Describe the possible benefits to the participants.

Participants will be given the opportunity to learn some physiology and biofluids content in an online format. They will also get the chance to apply their knowledge of physiology in exploring a topic for which some physiology knowledge is prerequisite - biofluids.

Benefits to Society
Describe the possible benefits to society.

In biomedical engineering, physiology is a core topic that is taught in different ways (different mathematical approaches and different course taxonomies). This study evaluates the possibility that different mathematical approaches and/or how the course topics are structured could lead to improved learning.

MINORS
Will minors be included as participants in this research?

○ *Yes* ◉ No

If yes, and the children are over the age of 11, you must upload an Assent Form under the Documents Tab.

In determining whether children are capable of assenting, the researcher must consider the age, maturity, and psychological state of the children involved in the study. Indicate how confidentiality will be maintained and attach all assent forms. Generally, written assent is required for minors over the age of eleven. The assent document should include all eight elements listed in Part VIII and be written in language appropriate for the age of the child. The research investigator is responsible for retaining all signed assent documents for at least seven years past the completion of the research activity.

ADDITIONAL INFORMATION

If you have any additional information that would be helpful to the IRB in making a determination with regards to this submission, please describe below.

Appendix J: MS Excel Data Collection Spreadsheet

PARTICIPANT PROTOCOL	ASSESSMENT OBJECTIVE	Outcomes Assessment	
		Evidence	Where found?
Avatar Name			
Meet with researcher face-to-face to introduce study, participant chooses avatars and gets passwords			
Gender	DEMOGRAPHICS		
Age			
Native English speaker			
Year in School (Semester classification)			
Major			
Enjoy problem-solving aspects of engineering			
Interested in biomedical engineering			
Interested in human and animal physiology			
Calculus @ UW-Madison			
Last Calculus course completed or in progress			
Enjoy Algebra?			
Enjoy Calculus?			
Enjoy Statistics?			
HS-Chem 1			
HS-Chem 2			
HS-AP Chem			
HS-Org Chem			
HS-Biol 1			

HS-Biol 2			
HS-AP Biol			
HS-Physiology			
HS-Gen Physics			
HS-Math Physics			
HS-Other			
Univ-Gen Chem			
Univ-Analytical Chem			
Univ-Org Chem 1			
Univ-Org Chem 2			
Univ-Animal Biology			
Univ-Gen Physics			
Univ-Physiology			
Univ-Other			
Enjoy Chemistry?			
Enjoy Physics?			
Enjoy Biology?			
Weekly computer use (time in hrs)			
Played or worked in MUVE			
Taken an online course			
Taken a Blended course			
Taken an eCOW2 course			
Initial Logon to Second Life			
Initial Logon to Moodle site			
Review Physiology Learning Objectives	HPL	Review? Yes/No	Activity Report
Physiology Pre-test	HPL	Time on Pre-test	Quiz Report
Physiology Pre-test Q1	Student will recognize the main points of cell theory	**Correct? Yes (1) /No (0)**	Quiz Report (Rubrics)
Physiology Pre-test Q2	Student will compare and contrast the structure and function of the four major tissue types	**Score? 1 - 4**	
Physiology Pre-test Q3	Student will analyze a hematocrit value	**Correct? Yes/No**	
Physiology Pre-test Q4	Student will cite examples of the function of blood	**Score? 1-5**	
Physiology Pre-test Q5	Student will differentiate blood vessels by elasticity	**Correct? Yes/No**	
Physiology Pre-test Q6	Student will assess effects of capillary filtration given changes in typical pressures	**Score? 1 - 4**	

Physiology Pre-test Q7	Student will summarize function of blood-brain barrier	**Correct? Yes/No**	
Review Physiology Glossary	HPL	Physiology Glossary Review? #	Activity Report
Review Cell Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete Cells Lesson	HPL	Time on Lesson	Activity Report
	HPL	Glossary view during lesson	Activity Report
	HPL	Lesson Questions Overall Score	Lesson Report
	HPL	Review Homeostasis Reading? Y/N	Activity Report
	HPL	Review Functional Compartments Reading? Y/N	Activity Report
	HPL	Membrane Transport Question Correct? Yes/No	Lesson Report
	HPL	Review Diffusion Video? Y/N	Activity Report
	HPL	Diffusion Question Correct? Y/N	Lesson Report
	HPL	Filtration Question Correct? Y/N	Lesson Report
	HPL	Review Facilitated Diffusion Video? Yes/No	Activity Report
		Facilitated Diffusion Question Correct? Yes/No	Lesson Report
	HPL	Review Mass Balance and Homeostasis Reading? Y/N	Activity Report
	HPL	Review Membrane Transport Video? Y/N	Activity Report
Complete Cells Lesson Review Questions	HPL	Time on Review Questions	Quiz Report
	HPL	Review Questions Overall Score	Quiz Report
	Recognize the main points of Cell Theory	Cell Theory Review Question Score? (out of 6)	Quiz Report
	Describe the structures of the cell membrane	Membrane Structure Review Question Correct? Yes/No	Quiz Report
	Describe the functions of the cell membrane	Membrane Function Review Question Correct? Yes/No	Quiz Report
	Describe the various mechanisms that cells use to transport substances across the cell membrane	Membrane Transport Review Question Score? (out of 6)	Quiz Report
Review Tissue Lesson Objectives	HPL	Review? Yes/No	Activity Report

Complete Tissue Lesson	HPL	Time on Lesson	Activty Report
	HPL	Glossary view during lesson	Activity Report
	HPL	Lesson Questions Overall Score	Activity Report
	HPL	Review Phys Systems Reading? Y/N	Activty Report
	HPL	Review Function and Process reading? Y/N	Activty Report
		Epithelial Tissue Question Correct? Y/N	Lesson Report
		Connective Tissue Question Correct? Y/N	Lesson Report
		Intercalated Disk Question Correct?	Lesson Report
		Review Nerve Transmission Video? Y/N	Activity Report
		Neural Cell Transmission Question Correct?	Lesson Report
Complete Tissue Lesson Review Questions		Time on Review Questions	Quiz Report
		Review Questions Overall Score	Quiz Report
	Identify the four major tissue types	Recognize Tissue Type Question Score? (out of 4)	Quiz Report
	Compare the structures of the four major tissue types	Tissue Structure Question Score? (out of 4)	Quiz Report (Rubric)
	Summarize major functions of four major tissue types	Recognize Tissue Function Question Score? (out of 4)	Quiz Report
Review Heart Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete Heart Lesson	HPL	Time on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
		Lesson Questions Overall Score	Lesson Report
	HPL	Overview of CV System Reading? Y/N	Activity Report
		Myocardium Question Correct? Y/N	Lesson Report
	HPL	Heart Anatomy Video? Y/N	Activity Report
	HPL	Cardiac Muscle Reading? Y/N	Activity Report
	HPL	Heart as Pump Reading? Y/N	Activity Report
		Conducting System of Heart Video? Y/N	Activity Report
	HPL	Cardiac Cycle Video? Y/N	Activity Report

		Atria/Ventricular Pressure Question Correct? Y/N	Lesson Report
	HPL	Blood Pressure Reading? Y/N	Activity Report
		Cardiac Cycle Question Correct? Y/N	Lesson Report
Complete Heart Lesson Review Questions		Time on Review Questions	Quiz Report
		Review Questions Overall Score	Quiz Report
		Heart Anatomy Question Score? (out of 2)	Quiz Report
	Identify blood vessels, chambers and valves of heart	Chambers and Valves Question Score? (out of 12)	Quiz Report
	Trace flow of blood through the heart	Blood Flow Through Heart Question Correct? Y/N	Quiz Report
	Explain the events of the cardiac cycle	Cardiac Cycle Question Correct? Y/N	Quiz Report
		BP Regulation Question Correct? Y/N	Quiz Report
	Define and describe factors that influence cardiac output and stroke volume	Stroke Volume Question Correct? Y/N	Quiz Report
Review Lung Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete Lung Lesson	HPL	Time on Lesson	Lesson Report
		Lesson Questions Overall Score	Lesson Report
		Glossary view during Lesson	Activity Report
		The Respiratory System Reading? Y/N	Activity Report
	HPL	Review Respiration Video? Y/N	Activity Report
	HPL	Alveoli Tissue Question Correct? Y/N	Lesson Report
		Gas Laws Reading? Y/N	Activity Report
	HPL	Review Boyle's Law Video? Y/N	Activity Report
		Intrapulmonary pressure Question Correct? Y/N	Lesson Report
		Diffusion of Solubillity of Gases Reading? Y/N	Activity Report
	HPL	Gas Exchange in Lungs and Tissues Reading? Y/N	Activity Report

		Gas Exchange Video Review? Y/N	Activity Report
		Oxygen Diffusion Question Correct? Y/N	Lesson Report
		Gas Transport Reading? Y/N	Activity Report
		Carbon Dioxide Transport Video Review? Y/N	Activity Report
Complete Lung Lesson Review Questions		Time on Review Questions	Quiz Report
		Review Questions Overall Score	Quiz Report
	Describe the processes of external respiration	External Respiration Question Correct? Y/N	Quiz Report
	Identify structures of the respiratory system	Respiratory Structure Question Score? (out of 4)	Quiz Report
	Trace flow of air through the pulmonary circuit	Pulmonary Circuit Question Correct? Y/N	Quiz Report
	Explain how pressure gradients affect the flow of air in the respiratory system	Pressure Gradient Question Score? (out of 2)	Quiz Report
	Describe the process of diffusion of gases at the alveoli	Alveolar Diffusion Question Correct? Y/N	Quiz Report
	Compare and contrast gas exchange at the lungs and gas exchange at the tissues	Gas Exchange Question Score? (out of 2)	Quiz Report
	Describe the role of chemoreceptors and baroreceptors as sensors that maintain homeostasis	Chemoreceptor/Baroreceptor Question Correct? (out of 2)	Quiz Report
	Describe the process of internal respiration	Internal Respiration Question Correct? Y/N	Quiz Report
Review Blood Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete Blood Lesson	HPL	Time on Lesson	Lesson Report
		Overall Score on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
	HPL	pH Level Question Correct? Y/N	Lesson Report
		Red Blood Cells Reading? Y/N	Activity Report
	HPL	Platelets and Coagulation Reading? Y/N	Activity Report
		Red Blood Cells Question Correct? Y/N	Lesson Report
	HPL	Plasma and Cellular Elements Reading? Y/N	Activity Report

		Plasma Viscosity Question Correct? Y/N	Lesson Report
	HPL	Blood Functions Video? Y/N	Activity Report
Complete Blood Lesson Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
	Identify individual components of blood and their functions	Formed Element Question Score? (out of 9)	Quiz Report
	Differentiate between elements of plasma	Plasma Composition Question Correct? Y/N	Quiz Report
	Explain changes in hematocrit levels	Hematocrit Analysis Question Score? (out of 2)	Quiz Report
	Identify major functions of blood	Blood Function Question Correct? Y/N	Quiz Report
Review Vessel Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete Vessel Lesson		Time on Lesson	Lesson Report
		Overall score on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
	HPL	Blood Vessels Reading? Y/N	Activity Report
	HPL	Resistance in Arteriole Reading? Y/N	Activity Report
		Vasoconstriction Question Correct? Y/N	Lesson Report
	HPL	Distribution of Blood Reading? Y/N	Activity Report
	HPL	Exchange at Capillaries Reading? Y/N	Activity Report
		Capillary pressure question correct? Y/N	Lesson Report
	HPL	Capillary exchange Video? Y/N	Activity Report
		Blood vessel order question correct? Y/N	Lesson Report
Complete Vessel Lesson Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
	Identify blood vessel types by their functions	Blood vessel Function Question Score? (out of 7)	Quiz Report
	Distinguish between blood vessel types based on their structure	Blood vessel Structure Question Correct? Y/N	Quiz Report

	Identify major blood vessels when shown a diagram	Head and Neck Vessels Question Score? (out of 10)	Quiz Report
	Distinguish between capillary exchange processes that occur in the brain and those that occur in other tissues in the body	Capillary Exchange Question CorrectY/N	Quiz Report
	Distinguish metarterioles from anastomoses based on function	Metarteriole Question Correct? Y/N	Quiz Report
Review CNS Lesson Objectives	HPL	Review? Yes/No	Activity Report
Complete CNS/ANS Lesson		Time on Lesson	Lesson Report
		Overall Score on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
	HPL	Anatomy of CNS Reading? Y/N	Activity Report
		Choroid Plexus Question Correct? Y/N	Lesson Report
		Brain Capillary Question Correct? Y/N	Lesson Report
	HPL	Baroreceptor reflex video? Y/N	Activity Report
	HPL	Regulation of blood pressure reading? Y/N	Activity Report
Complete CNS/ANS Lesson Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
	Describe how cerebrospinal fluid protects the brain	Cerebrospinal Fluid Question Score? (out of 3)	Quiz Report
	Describe the structure of the blood-brain barrier	Blood-Brain Barrier Question Correct? Y/N	Quiz Report
	Recognize that cerebral blood flow must remain constant to meet the energy demands of the brain	Cerebral Blood Flow Question Correct?	Quiz Report
	Describe the role of mechanoreceptors in biological transduction	Biological Transduction/ Mechanoreceptor Question Correct? Y/N	Quiz Report
	HPL	Time on Post-test	Quiz Report
Physiology Post-test Q1	Student will recognize the main points of cell theory	**Correct? Yes /No**	Quiz Report (Rubrics)
Physiology Post-test Q2	Student will compare and contrast the structure and function of the four major tissue types	**Score? 1 - 4**	

Physiology Post-test Q3	Student will analyze a hematocrit value	**Correct? Yes/No**	
Physiology Post-test Q4	Student will cite examples of the function of blood	**Score? 1 - 5**	
Physiology Post-test Q5	Student will differentiate blood vessels by elasticity	**Correct? Yes/No**	
Physiology Post-test Q6	Student will assess effects of capillary filtration given changes in typical pressures	**Score? 1 - 4**	
Physiology Post-test Q7	Student will summarize function of blood-brain barrier	**Correct? Yes/No**	
	HPL	Time on Pre-test	Quiz Report
Engineering Pre-test Q1	Define hydrostatic pressure	Score? 1-2	Quiz Report
Engineering Pre-test Q2	Apply hydrostatic pressure equation to make predictions	Score? 1-2	Quiz Report
Engineering Pre-test Q3	Define allometric scaling	Score? 1-2	Quiz Report
Engineering Pre-test Q4	Explain how dimensional analysis could be used to solve a given problem	Score? 1-4	Quiz Report
Engineering Pre-test Q5	Describe transmural pressure and its relationship to absolute pressure	Score? 1-2 (Rubric)	Quiz Report
Engineering Pre-test Q6	Apply LaPlace's Law to interpret physiological changes	Correct? Y/N	Quiz Report
Engineering Pre-test Q7	Recognize equations that model biofluid flow	Correct? Y/N	Quiz Report
Engineering Pre-test Q8	Differentiate between Newtonian and Non-Newtonian biofluids flow	Score? 1-2	Quiz Report
Review Biofluids Challenge Objectives	HPL	Review? Yes/No	Activity Report
Review Biofluids Glossary	HPL	Review? Yes/No	Activity Report
Online Meeting Scheduler			

Initial Thoughts Questionnaire	List physiology systems and concepts that you predict will be involved in developing a response to Mrs. Howell's concerns.	Rubric	Activity Report
	Of the topics you listed above, which will be the three most important for this challenge.	Most Important	Activity Report
		Secondmost	
		Thirdmost	
	In the Zumahavi Resource Library, information is available on each of the topics below. Select the three (3) topics you think will be most important in solving the challenge.	Important topic 1	Activity Report
		Important topic 2	
		Important topic 3	
Posts in Zumahavi Forum	**Qualitative Data - Post Dissertation Analysis**	Rubric	Zumahavi Discussion Forum
Second Life Brainstorming Meeting	**Qualitative Data - Post Dissertation Analysis**		Script from SecondLife Conference
Wiki Development	**Qualitative Data - Post Dissertation Analysis**		Moodle Course Page
Review Cardiovascular System Basics Lesson Objectives Complete		Review? Y/N	Activity Report
		Time on Lesson	Activity Report

Cardiovascular System Basics Lesson		Overall Score on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
		Adaptation of Giraffe CV Question Correct? Y/N	Lesson Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Recognize cellular homeostasis	Lesson Report
	XFR_01	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
		Pressure measurement Question Correct? Y/N	Lesson Report (Rubric)
		Hydrostatic Pressure Question Correct? Y/N	Lesson Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Compare and contrast structure/function relationship (out of 4)	Lesson Report (Rubric)
	XFR_02	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
		Giraffe Blood Pressure Question Correct? Y/N	Lesson Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Differentiate blood vessels based on their elasticity	Lesson Report
	XFR_05	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
Complete Cardiovascular System Basics Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
		Giraffe Pressure Transducer Question Correct? Y/N	Quiz Report

		Hydrostatic Pressure Factors Question Correct? Y/N	Quiz Report
		Applying Hydrostatic Pressure Question Correct? Y/N	Quiz Report
Review Scaling and Cardiovascular Anatomy Lesson Objectives			Activity Report
Complete Scaling and Cardiovascular Anatomy Lesson		Time on Lesson	Lesson Report
		Overall Score on Lesson	Lesson Report
		Glossary view during Lesson	Activity Report
		Comparative Giraffe CV System Question Correct? (out of 4)	Lesson Report (Rubric)
	PHYSIOLOGY TRANSFER OBJECTIVE	Analyze a hematocrit value	Lesson Report
	XFR_03	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Cite functions of blood (out of 5)	Lesson Report
	XFR_04	***question view***	
		next view	
	TIMING	Time on Question	Activity Report
		Allometric Scaling Question Correct? Y/N	Lesson Report
		Giraffe Heart Weight Scaling Question Correct? Y/N	Lesson Report

		Giraffe CV System Adaptions Question Correct? Y/N	Lesson Report
Complete Scaling and Cardiovascular Anatomy Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
		Isometric scaling question correct? (out of 2)	Quiz Report
		Pi-Theorem Question correctt? (out of 2)	Quiz Report
		Giraffe CV System Correct? (out of 7)	Quiz Report
Review Capillary and Cerebral Perfusion Lesson Objectives		Review? Y/N	Activity Report
Complete Capillary and Cerebral Perfusion Lesson		Time on Lesson	Lesson Report
		Overall Score on Lesson	Lesson Report

		Glossary view on Lesson	Activity Report
		Giraffe CV SyStem Question Correct? Y/N	Lesson Report
		Starling Pressure Question Correct? (out of 8)	Lesson Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Capillary Filtration Question Correct? (out of 4)	Lesson Report
	XFR_06	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
	PHYSIOLOGY TRANSFER OBJECTIVE	Blood-Brain barrier Question Correct? Y/N	Lesson Report
	XFR_07	***question view***	
		next view	
	TIMING	Time on Question [sec]	Activity Report
Complete Capillary and Cerebral Perfusion Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
		Transmural Pressure Question Correct? (out of 2)	Quiz Report
		Laplace Law Question Correct? Y/N	Quiz Report
Review Fluid Flow Lesson Objectives		Review? Y/N	Activity Report
Complete Giraffe Fluid Flow Lesson		Time on Lesson	Lesson Report
		Overall Score on Lesson	Lesson Report
		Glossary view on Lesson	Activity Report
		Shear rate and viscosity question correct? Y/N	Lesson Report
Complete Giraffe Fluid Flow Review Questions		Time on Review Questions	Quiz Report
		Overall Score on Review Questions	Quiz Report
		Poiseuille Question Correct? Y/N	Quiz Report

		Blood Fluid Question Correct? (out of 3)	Quiz Report
Resource Library - Items Viewed		Giraffes and okapis	Activity Report
		Venous valves in the giraffe, okapi, camel and ostrich	Activity Report
		The physiology of the giraffe	Activity Report
		Heart anatomy of Giraffa camelopardalis rothschildi	Activity Report
		Observations on the structure and innervation of the presumptive	Activity Report
		Circulation and respiration in the giraffe	Activity Report
		Some aspects of the cardiovascular system in giraffe	Activity Report
		Circulation of the giraffe	Activity Report
		Hypertension and counter-hypertension mechanisms	Activity Report
		Blood pressure responses of wild giraffes	Activity Report
		Some reflections on today's hypertension research	Activity Report
		The origin of mean arterial and jugular venous blood pressures	Activity Report
		Blood flow and pressure in the giraffe carotid artery	Activity Report
		The cerebreal blood supply in the Giraffidae	Activity Report
		Giraffes, siphons, and starling resistors: Cerebral perfusion	Activity Report
		How does the blood leave the brain?	Activity Report
		The vertebral venous plexus as a major cerebral venous outflow	Activity Report
		Protection of the cerebral circulation by the CSF	Activity Report
		Model analogues in the study of cephalic circulation	Activity Report
		Developmental adaptations to gravity in animals	Activity Report
		Gravity and the circulation	Activity Report
		Living in a physical world VII	Activity Report
		Factors affecting cerebral circulation	Activity Report
		How giraffe adapt to their extraordinary shape	Activity Report

		Cerebral hemodynamics in the giraffe	Activity Report
		Cerebral autoregulation: an overview of current concepts	Activity Report
		Blood flow uphill and downhill: Does a siphon facilitate circulation	Activity Report
		Biofluid mechanics in flexible tubes	Activity Report
		Autoregulation and haemodynamics of giraffe carotid blood flow	Activity Report
		Gravitation haemodynamics and oedema prevention in giraffe	Activity Report
		Cerebral perfusion pressure in giraffe: Modelling effects	Activity Report
		The principle of laplace and scaling	Activity Report
		Syncope and fainting	Activity Report
		Fainting in animals	Activity Report
Second Life Brainstorming Meeting	**Qualitative Data - Post Dissertation Analysis**		
Final Thoughts Questionnaire	**Qualitative Data - Post Dissertation Analysis**		
		Time on Post-test	
Engineering Post-test Q1	Define hydrostatic pressure	Score? 1-2	
Engineering Post-test Q2	Apply hydrostatic pressure equation to make predictions	Score? 1-2	
Engineering Post-test Q3	Define allometric scaling	Y/N	
Engineering Post-test Q4	Explain how dimensional analysis could be used to solve a given problem	Score? 1-4	
Engineering Post-test Q5	Describe transmural pressure and its relationship to absolute pressure	Score? 1-2	
Engineering Post-test Q6	Apply LaPlace's Law to interpret physiological changes	Y/N	
Engineering Post-test Q7	Recognize equations that model biofluid flow	Y/N	
Engineering Post-test Q8	Differentiate between Newtonian and Non-	Score? 1-2	

	Newtonian biofluids flow		
Total time spent on study			
Characterize the Time Spent			
Valuable activities to solve challenge			
MOST Valuable activity			
When F2F meetings NOT possible, discussion forums are effective collaborative tool.			
When F2F meetings NOT possible, wikis are effective collaborative tool.	DEBRIEFING SURVEY		
When F2F meetings NOT possible, meetings in Second Life are effective collaborative tool.			
When F2F meetings ARE possible, discussion forums are effective collaborative tool.			
When F2F meetings ARE possible, wikis are effective collaborative tool.			
When F2F meetings ARE possible, meetings in Second Life are effective collaborative tool.			
I gained useful information about Physiology Systems that I can apply to future learning in engineering.			

I gained useful information about Physiology Concepts that I can apply to future learning in engineering.		
I gained useful information about Biofluids that I can apply to future learning in engineering.		

Appendix K: Qualitative Study IRB Protocol

University of Wisconsin-Madison **Application for Initial Review of Research Projects Involving Human Subjects** Social and Behavioral Sciences IRB	**For Office Use Only** **Protocol #: SE-2012-0059** **Date Received: 1/31/2012**

General Protocol Information and Personnel Information

General Protocol Information

Current Protocol Title
Qualitative Assessment of How Biomedical Engineering Undergraduate Students Transfer Physiology Knowledge

Current Principal Investigator
Naomi C Chesler, Biomedical Engineering

Expected Project Starting Date (mm/dd/yyyy):
2/23/2012

Expected Project Duration:
12 months

If this research is part of a previously approved project or is related to another project, please provide the other protocol number(s) and approval date(s) and indicate whether this is a Five (5) Year Renewal?
Research is related to Protocol SE-2008-0754 (ACTION: Exempt 2/4/2009)

Please select the type of review you are requesting:

- (•) Application for Initial Review
- ( ) Application for Protocol Development Activities Only

Registration of Research Studies

If you will be publishing your research in a member journal of the International Committee of Medical Journal Editors (ICMJE) or in a publication that adheres to the standards of the ICMJE, you may need to register your study at Clinicaltrials.gov. Specific information about ICMJE's registration requirements is available on the ICMJE website: http://www.icmje.org/index.html#clinicaltrials

If you have any questions about the ICMJE registration requirement, contact the UW-Madison Office of Research Policy at 608-265-2800 or email researchpolicy@uwmad.wisc.edu

Personnel Information

Conflict of Interest Questions

Does ANY member of the study team involved in the design or conduct of the research study, or their immediate family (this includes spouse and dependent children) have interests related to the research that meet or exceed one of the following thresholds:

a) Compensation of $20,000 or more in a calendar year from a business entity

b) An ownership interest in a publicly traded business entity valued at $20,000 or more or a 5% or greater equity interest

c) Any ownership interest in a privately held business entity

d) A leadership position in a business entity, i.e., positions with fiduciary responsibilities, including senior managers (e.g., presidents, vice presidents, etc.) and members of boards of directors and trustees. (Scientific advisory board membership is not a leadership position.)

e) A proprietary interest in the research such as royalties, patents, trademarks, copyrights, or licensing agreements, including any agent, device or software being evaluated as part of the research study. **[Do not include those managed by the Wisconsin Alumni Research Foundation (WARF)]**

○ Yes ◉ No

If yes, identify the personnel who have this interest and include copies of any management plans or documentation of exceptions granted by the UW-Madison Conflict of Interest Committee to allow the personnel to participate in this study:

Does ANY member of the study team involved in the design or conduct of the research study, or their immediate family (this includes spouse and dependent children) have a financial interest that requires disclosure to the sponsor or funding source?

Yes No

If yes, identify the personnel who have this interest:

Does ANY member of the study team receive incentives for recruiting human subjects or for any other purpose directly related to the study?

Yes No

If yes, please identify the personnel and describe the nature of the incentives.

HIPAA Health Care Component

Are you in the HIPAA Health Care Component of the UW-Madison or within the Affiliated Covered Entity AND are you using Protected Health Information (individually identifiable health information)?

Yes No

Are you outside of the HIPAA Health Care Component but are using Protected Health Information (individually identifiable health information) from a HIPAA Covered Entity?

Yes No

If yes to either of the HIPAA questions, you are required to take the HIPAA Research Training Module. You will not be able to submit your protocol until the training is completed. Any questions about HIPAA Training should be directed to the UW-Madison HIPAA Privacy Officer.

Human Subjects Protection Training

All researchers (including students and non-UW-Madison personnel) on this protocol must complete Human Subjects Protection Training.

UW-Madison personnel must take UW-Madison's CITI Human Subjects Protection Training.

Note: Please allow 24 hours after completion of the training before attempting to submit the protocol. Information in WebKit as to who has completed the human subjects training is updated nightly.

Does the research involve any non-UW-Madison researchers (including key personnel)?

○ Yes ◉ No

If yes, non-UW-Madison personnel may take UW-Madison's CITI Human Subjects Protection Training or may take the equivalent training required by their home institution, e.g., CITI training or NIH Human Subjects training.

If any non-UW-Madison personnel on this protocol **DO NOT** take UW-Madison's CITI training, you **MUST** do the following before a protocol can be submitted:

- Email a certificate of their alternative training to the IRB Office for review **PRIOR** to submission of the protocol. The IRB Office must manually enter the training date into WebKit before the protocol can be submitted.
- After emailing the alternative training certificate(s) to the IRB Office, upload any alternative training certificates on the Documents Tab.

Collaborative Research Studies

1) Does this study involve any research personnel who do not hold an appointment, are not employed, or are not a student at UW-Madison?

○ Yes ◉ No

a) Are any research personnel employed by another institution or organization that HAS ITS OWN institutional review board (IRB) for human subjects research?

○ Yes ◉ No

i) If yes, please upload the other IRB(s)' approval of this protocol (or evidence that this protocol has been submitted to the other IRB(s) for review) on the Documents Tab.

Note: Research personnel employed by another institution or organization whose IRB has approved the protocol should NOT be listed as key personnel on the UW-Madison protocol. Instead, these individuals should be listed as key personnel on the other institution's protocol.

b) Are any research personnel employed by an organization or institution that does not have its own IRB?

( ) Yes (•) No

i) If yes, please list these individuals and their organizations and institutions and their role in the research study:

ii) Also, please list these individuals in the Study Personnel section of the protocol form and choose "Other" for their Job Category and Department.

Note: If you will be collaborating with individual(s) from another institution or organization, additional steps may be required. Please contact your IRB Office for more information.

Protocol Resources
By checking each of the boxes below, Principal Investigators assure the IRB that the following criteria are met with respect to each protocol.

- [x] Adequate resources, including funding, facilities, staff, and equipment, exist to conduct the research.
- [x] All personnel performing any procedures associated with this research study have appropriate expertise, and if applicable, proper licensure and/or credentials to do so.

Study Personnel
Use **"Other"** if a person's department or agency is not in list of Departments.

Project Personnel

Dr. Naomi C. Chesler, Ph.D. Biomedical Engineering 1550 Engineering Dr 2146 ECB	Principal Investigator chesler@engr.wisc.edu 608-265-8920
Regina K. Nelson Biomedical Engineering 431 Wendt Commons 215 N. Randall Avenue	Co-Investigator reginanelson@wisc.edu 608-890-2109

Project Sponsorship Information (current or planned)

1) Is this research to be funded with a grant or contract from a federal, non-federal, or private sponsor?

( ) Yes (•) No

2) Is the research to be funded with federal funds, or are federal funds being applied for?

( ) Yes (•) No

If yes, what is the status of this federal proposal?

If yes, upload the grant proposal on the Documents tab.

Note: If you are submitting a **stem cell protocol,** you need to submit your **grant abstract,** not the entire grant proposal.

3) Is the research to be funded by a private or non-federal sponsor? (This includes University of Wisconsin and the State of Wisconsin)

( ) Yes (•) No

4) If there is no grant or contract to fund this research, how will this research be funded?
Personal funds of graduate student completing the dissertation research.

Sponsor Information

For each current or potential funding source, provide:
a. The name of the sponsoring agency (including UW funding)
b. The UW proposal number
c. The UW grant fund and account number (i.e. 144-abxx)
d. The agency award number

Sponsor	Proposal #	Fund Acct #	Agency Award #

Review Type and Questionnaire

Review Type

Request for a

(•) Exempt Review

Expedited Review

Full Review

The IRB Office will make the final determination of what type of review your project will get.

<u>Questionnaire</u>

Please answer *all* of the questions below.

1) Does the research involve genetic testing or DNA samples collected from, e.g., blood, saliva, hair, nail clippings, or bodily fluids?

Yes No

2) Does the research involve **the collection of data** concerning:

a) Prisoners?

Yes No

b) Fetuses, neonates or pregnant women?

Yes No

c) Participants with impaired decision-making capacity, e.g., the cognitively impaired?

Yes No

If yes to Question 2.c., are there

i) Procedures for assessing capacity and reassessing capacity, if participation is ongoing?

N/A

No

Yes

ii) Procedures for obtaining surrogate consent, when appropriate.

N/A

No

Yes

iii) Procedures for identifying legally authorized representatives for consent, when appropriate.

N/A

No

Yes

iv) Procedures for obtaining assent, when appropriate.

N/A

No

Yes

If assent will be obtained, you must upload an Assent Form on the Documents Tab. You must also upload a consent form for legally authorized representative(s).

d) Participants who are institutionalized (e.g., in a mental health facility, nursing home, or halfway house)?

Yes No

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3) Will the study elicit data about participants engaged in illegal or stigmatizing behaviors (e.g., illicit drug use, child abuse, alcoholism, or gambling)?

Yes No

If yes, provide an explanation in the study description.

---

4) Does the research involve deception of the participants by the researcher?

Yes No

If **yes**, upload a debriefing statement explaining the deception under the Documents tab.

---

5) Does the research involve:

a) Observations of behavior of participants under the age of 18 outside of an established educational setting?

Yes No

b) Survey or interviews of subjects under the age of 18?

Yes No

Note: If you answered YES to any part of questions 1-5, your research is subject to full review by a human subjects committee. Please check Full Review above.

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6) Does the research involve the **collection of data** from participants with:

a) Learning disabilities?

Yes No

b) Emotional disabilities?

Yes No

c) Developmental disabilities?

Yes No

d) Physical disabilities?

Yes No

---

7) Does the research involve:

a) Students in a classroom setting?

Yes No

b) Collection of images or audio recordings of the participants?

Yes No

If yes, please provide information in the Study Description how the recordings will be used, how long they will be kept, who will see/ hear the recording(s) and where the recording(s) will be used (e.g., in a classroom, professional meeting, etc.)?

c) Only the use of existing data (i.e., no human subject contact)?

Yes No

If yes, please provide information in the Study Description on the source of the data, whether the data is publicly available and whether the data contains direct or indirect identifiers.

d) Participants who have a status relationship with the researchers (e.g., students or employees)?

Yes No

If yes, please provide information in Study Description.

e) Participants who are illiterate

Yes No

If yes, upload the oral consent script on the Documents Tab.

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8) Will the study target or exclude a particular gender or ethnic or racial group?

Yes No

If yes, please provide justification in Study Description.

---

9) Will the research be conducted outside of the United States?

Yes No

Study Description

Please supply the information requested below in lay terms (non-technical language).

WARNING!!! The form has a restriction on how many characters will be saved. If you enter more than 2000 characters in any text box, you will lose your data. Pay attention to your word count limit.

ABSTRACT

In lay terms **using 300 words or less (no more than 2000 characters),** please describe the GENERAL PURPOSE of the study and how human participants will be involved. List the SPECIFIC AIMS and HYPOTHESES or RESEARCH QUESTIONS.

This study is a follow-up to a previous study approved by the Education Research IRB (Protocol SE2008-0754). The purpose of the proposed study is to do a qualitative case study analysis on a subgroup of the participants who completed the previous study that examined how engineering students learn physiology and biofluids in an online, challenge-based environment. This learning module was not part of any University course. Students did not receive credit for completing the modules nor was there a status relationship between the participant and researcher. Six participants will be followed, three who performed well in the previous study and three who struggled in the online environment. The participants will be chosen based on their Index of Adaptive Expertise score which was aggregated by activity and participation scores in the previous study. We hypothesize that there will be distinct differences in the learning profile for these two groups of participants. This study aims to uncover details of these learning profiles that might inform how undergraduate engineering students are taught. To perform a qualitative case study to analyze these differences, we will use the data collected in the previous study for each of the participants. In addition, participants will complete an online survey and follow-up interview in which questions will be asked to assess and evaluate how students learn different topics.

STUDY DESIGN AND METHODS

Inclusion Criteria

Outline the inclusion criteria for participants, explaining the rationale for the involvement of any special groups, e.g., prisoners, pregnant women, participants with impaired decision-making capacity and non-English speaking participants.

Participants in the study (n= 6) will be selected from participants who completed a previous study (Protocol SE2008-0754) where the participants were students in the College of Engineering at the University of Wisconsin-Madison who had not yet taken a college-level physiology course, but had taken at least two semesters of college-level calculus.

Explain how and where participants will be identified, recruited or the sampling procedures.

In the previous study (Protocol SE2008-0754), data were analyzed and an Adaptive Expertise Index (AdEX) score determined for each participant. In this proposed study, students whose ADEX scored fell in the top 10th percentile or bottom 10th percentile comprise the population from which six participants will be selected, 3 from the top and 3 from the bottom. All recruitment and consent tasks will be handled by doctoral student Regina Nelson, who does not have a status relationship with the participants.

Describe the characteristics of the targeted participants, including gender, age ranges, ethnic background and health/ treatment status.

The targeted population includes undergraduate students in the College of Engineering who have taken at least two semesters of calculus, never taken a college or AP physiology course, and participated in a previous study (Protocol SE2008-0754) where they scored in the top or bottom 10th percentile.

Number of Participants

Enter the number of participants you anticipate including from each targeted group listed above. A range is acceptable. NOTE: This is the number of subjects for which IRB approval will be granted. Prior IRB approval is required if additional participants are to be enrolled.

6 participants

Justify the number of participants (sample size) entered above.

This follow-on study involves using a qualitative case study approach to further analyze how engineering students learn. By selecting this small subset (n=6) of students, a thorough analysis can be made. The sample size is large enough to provide valuable insight that can be generalized to the population.

Role of Participants

Describe the role of participants, including what they will be asked to do, for how long, where, and whether deception will occur.

During their participation in an earlier study, data were collected as students engaged in online learning modules. This existing data will be further analyzed in this case analysis study. Additionally, study participants will be asked to complete an online survey, then interviewed for one hour with follow-up questions. The questions for the online survey and the follow-up interview will be drawn from the online data of the existing group of students. As such, the exact questions cannot be predetermined. However, the nature of the questions is described in the attached Survey/Interview Topics document. The time involved will be approximately 1/2 hour for the online survey and 1 hour for the interview. There will be no deception involved.

Privacy and Confidentiality
Explain how participants' privacy interest will be protected.

Participants will complete the survey online. An interview in a private office will be conducted. Questions on both the survey and interview relate to learning styles, techniques and strategies. Participants will have the option to not answer a question for any reason.

Explain if and how confidentiality will be maintained.

Participants in the previous study were given a pseudonym/avatar name that they used for the study. This pseudonym will be carried forward in this proposed study. Only the co-investigator, Regina Nelson, knows the identity of the participant. Regina Nelson does not have a status relationship with any of the participants.

Use of Images and Audio Recordings
If the research study involves collections of images or audio recordings of participants, explain how the recordings will be used, how long they will be kept, who will see/ hear the recording(s) and where the recording(s) will be used (e.g., in a classroom, professional meeting, etc.)?

The 1 hour interviews will be recorded to allow for data transcription, coding and analysis. Only the researchers will hear the recordings. The recordings will be transcribed and held only as long as required by the IRB. The researchers are comfortable with destroying the recordings as soon as they have been transcribed.

Use of Existing Data
If the research involves use of existing data (i.e., no human subject contact), provide information on the source of the data, whether the data is publicly available and whether the data contains direct or indirect identifiers.

Existing data recently collected (Protocol SE2008-0754) will be analyzed as part of this study. The data is not publicly available. Because of the nature of this follow-on study, the data contains both direct and indirect identifiers, but only to a pseudonym, not the participant name.

Compensation
Describe any compensation the participants will receive, including course credit.

Participants will be given $30 cash for their participation in the study (i.e. completing the online survey and the one-hour interview).

Sites
Describe sites where this research will take place.
Participants will complete the survey on their own time via an Internet connection. The one-hour survey will take place in the co-investigator's office on campus.

Does the study involve participants from places such as schools, libraries, community organizations, health clinics, etc.?

Yes No

If **yes**, upload documentation of permission from the appropriate official at the site (e.g. superintendent of schools, library or community center director, clinic director) to conduct the research under the Documents tab.

Informed Consent

Consideration should be given to the most appropriate method of obtaining informed consent, taking into account the literacy level of the subjects and confidentiality concerns. In some cases, oral consent may be more appropriate than written consent because signing a consent form would put the participants at greater risk. Consent should always be obtained in the native language of the participants.

The consent form should contain no language through which the potential participant or legally authorized representative waives or appears to waive any of the participant's legal rights or releases or appears to release the investigator, sponsor, institution, or its agent from liability or negligence.

Note: The IRB encourages the use of the Consent Form Wizard.

a) Will written consent be used?

Yes No

b) Will oral consent be used?

Yes No

If yes to Question a or b, please upload the consent form and oral consent form script.

If oral consent is proposed, please justify the waiver of documentation of written consent. Please review the Common Rule provisions governing waiver of documentation of informed consent 45 CFR 46.117(c) and the UW-Madison guidance on Oral Consent /Waiver of Consent Documentation.

Who will obtain consent from participants?

Regina Nelson, the co-investigator, who does not have a status relationship with the participants.

Is the native language of the participants something other than English?

Yes No

If yes, upload on the Documents tab all consent forms, oral consent scripts and all supporting documents in the participants's native language and an English translation of each.

Measurement Procedures
Will any of the following be used as part of the study: questionnaires, measurement instruments, interview protocols, or a description of topics or an approximate script?

(•) Yes ( ) No

Describe all measurement procedures to be used in this study.

During their participation in an earlier study, data were collected as students engaged in online learning modules. This existing data will be further analyzed in this case analysis study. Additionally, study participants will be asked to complete an online survey, then interviewed for 1/2 hour with follow-up questions. The questions for the online survey and the follow-up interview will be drawn from the online data of the existing group of students. As such, the exact questions cannot be predetermined. However, the nature of the questions is described in the attached Survey/Interview Topics document.

If yes, please upload on the Documents tab all questionnaires, measurement instruments, interview protocols, or a description of topics or an approximate script.

If the study involves non-English speaking participants, upload all questionnaires, measurement instruments, interview protocols, or a description of topics or an approximate script in the participant's native language and an English translation of each.

Recruitment Materials
Will any of the following be used as part of the study: flyers, brochures, advertisements, or other recruitment materials?

( ) Yes (•) No

If yes, upload on the Documents tab all flyers, brochures, advertisements, or other recruitment materials.

If the study involves non-English speaking participants, upload all recruitment documents in the participant's native language and an English translation of each.

RISK/BENEFIT ASSESSMENT
Participants should be protected against injury and invasion of their privacy, and their dignity should be preserved. Risks fall under the following categories: physical, psychological, social, economic, legal, and other.

Risks
Are there risks to the participants?
( ) Yes (•) No

If yes, please assess the types and level of each type of risk involved in the research.

Steps to Minimize Risks
Describe the steps that will be taken to minimize risk.

Medical or Professional Intervention
Discuss provisions for ensuring necessary medical or professional intervention in the event of adverse effects to the participants or additional resources for participants.

Alternative Treatments
If appropriate, describe alternative treatments and procedures that might be advantageous to the participants.

Possible Benefits to the Participants
Describe the possible benefits to the participants. Note: Compensation paid to participants is NOT a benefit.

Although the undergraduate students participating in this research may not derive the immediate benefit of improvements to how engineering courses are delivered to college students, through the survey and interview process, they will have an opportunity to increase their meta-awareness of how they individually learn engineering topics.

Benefits to Society
Describe the possible benefits to society.

The more we learn about how engineering students learn and transfer that knowledge can improve how engineering courses are designed and delivered.

MINORS
Will minors be included as participants in this research?
○ Yes ◉ No

If yes, and the children are over the age of 11, you must upload an Assent Form under the Documents Tab. You must also upload a Consent Form for a legally authorized representative, e.g., parent or guardian.

In determining whether children are capable of assenting, the researcher must consider the age, maturity, and psychological state of the children involved in the study. Indicate how confidentiality will be maintained and attach all assent forms. Generally, written assent is required for minors over the age of eleven. The assent document should include all eight elements of consent listed in 45 CFR 46.116 and be written in language appropriate for the age of the child. The research investigator is responsible for retaining all signed assent documents for at least seven years past the completion of the research activity.

ADDITIONAL DOCUMENTS
Do you have additional documents for the IRB that are related to your research?

(•) Yes ( ) No

ADDITIONAL INFORMATION
If you have any additional information that would be helpful to the IRB in making a determination with regards to this submission, please describe below.

An additional document - Survey/Interview Topics has been attached.

Survey/Interview Question Topic List

The specific questions for the online survey will be determined by the cumulative data from the previous study of the six participants who are recruited for the current study and their online interview.

Additionally, the exact questions for each individual's survey will be a result of the cumulative data from the in-person interview.

Although the exact nature of the questions is not known, the following are topic areas that will be addressed:

- Strategies for taking online quizzes
- Strategies for engaging with online lessons
- Reasons for deciding to use supplemental material in online lessons (i.e. videos, additional reading, interactive tools)
- Preferable time of day for working on online lessons
- Previous online courses
- Preference for asynchronous or synchronous online activities
- Prerequisite knowledge of subject areas addressed in study (physiology and biofluids)
- Past experiences working with teams to solve a problem (both virtual and face-to-face)

Appendix L: Semi-structured interview schedule

<table>
<tr><td colspan="3">Ideally in a learner-centered environment, instructors would try to get a sense of what students know and can do as well as their interests and passions—</td></tr>
<tr><th>Main questions</th><th>Additional questions</th><th>Clarifying questions</th></tr>
<tr><td>Tell me about an experience in a specific class where you felt the instructor really “got” the students – understood their prior experiences and where they were at that point in their learning?

If there was an ideal environment for your learning style, how would you describe it?</td><td>Have you experienced a course where the opposite is true – the instructor did not understand where the students were at that point?

What would you like to have every instructor intuitively know about you at the beginning of each course?</td><td>▪ Can you expand a little on this?
▪ Can you tell me anything else?
▪ Can you give me some examples?
▪ How did that affect how you like to learn?
▪ What learning strategies did you use in that situation?</td></tr>
<tr><td colspan="3">Ideally, students should be able to do more than just repeat the steps that they learned in class but actually apply the knowledge to something meaningful and realistic. The challenge in creating this situation is balancing between activities designed to promote understanding and those that are designed to promote automaticity of skills.</td></tr>
<tr><th>Main questions</th><th>Additional questions</th><th>Clarifying questions</th></tr>
<tr><td>Consider the courses that you have taken that were prerequisites for future courses... have you had some that you felt better prepared you than others conceptually?

Consider the courses that you have taken that were prerequisites for future courses...have you had some that you felt better prepared you than others in being able to efficiently repeat what you learned?

One of the goals of the physiology training was to prepare you for the biofluids challenge. What part of the online physiology training was effective in preparing you to use your new physiology knowledge as you worked to solve the biofluids challenge?

Considering how you learn best, can you think of some of the ways that a learning environment can be set up to best help you prepare for future courses?</td><td>Can you describe a course that did not prepare you well for subsequent courses?

Do you have strategies to fill in gaps when you feel you are not well-prepared?

Where did you feel prepared or underprepared when working on the biofluids challenge?</td><td>▪ Can you expand a little on this?
▪ Can you tell me anything else?
▪ Can you give me some examples?
▪ How did that affect how you like to learn?
▪ What learning strategies did you use in that situation?</td></tr>
</table>

Ideally, assessments and feedback focus on understanding and not just memorizing procedures and facts. In order for feedback to be most valuable it needs to give students the opportunity to use it to revise their thinking as they are working on a unit or project.		
Main questions	**Additional questions**	**Clarifying questions**
What are your favorite types of learning assessments? How do you think assessment is different in online learning? What have you changes about your learning strategies when a course or a part of a course is online?	Do you have strategies for self-assessment as you learn? How do you decide when you need to learn more…when you need to fill in some gaps? As a student, what type of assessment is most effective for your learning style?	▪ Can you expand a little on this? ▪ Can you tell me anything else? ▪ Can you give me some examples? ▪ How did that affect how you like to learn? ▪ What learning strategies did you use in that situation?
Ideally in a community-centered environment, 1) real-world tasks are considered and connections are made between the classroom and the outside community and 2) students learn from one another.		
Main questions	**Additional questions**	**Clarifying questions**
Can you tell me about a course where you felt the real-world connections were made? Tell me about your favorite example working with a group on a learning task. Have you experienced collaboration activities in online courses that required you to use the Internet? Tell me about your experiences.	Can you describe a course where that did not happen? Tell me about your least favorite group or collaborative experience. How do your learning strategies differ when you work with a group?	▪ Can you expand a little on this? ▪ Can you tell me anything else? ▪ Can you give me some examples? ▪ How did that affect how you like to learn? ▪ What learning strategies did you use in that situation?