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Using Computer-based Online Learning Modules to Promote Conceptual Change: Helping Students Understand Difficult Concepts in Thermal and Transport Science*

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Misconceptions about engineering and science concepts persist among engineering students, and some are resistant even to direct instruction. This paper reports on a unique form of computer-based online learning module, designed to help engineering undergraduates learn difficult concepts in the thermal and transport sciences (specifically, heat transfer, mass diffusion, and microfluidics). The design of these modules has been informed by relevant research on cognitive psychology and technology-enhanced learning. Specifically, the modules are based on the prior work of Chi and Slotta, which focuses on helping students understand the emergent properties of complex physical systems, thereby providing a means for promoting conceptual change within these challenging domains. The modules were designed and hosted in a Web-based learning management system, where a variety of interactive materials and inquiry prompts were incorporated to help students better understand the concepts and visualize the phenomena. Engineering students' perceptions of computer-based online learning are reported along with learning outcomes that resulted from their use of the modules. This was the first study to provide a discipline-based example in engineering education for how to use computer-based online learning and emergent properties of complex systems to help undergraduate engineering students learn difficult concepts. It has implications for (1) designing effective online learning environments to help students learn difficult science and engineering concepts; and (2) developing effective instructional strategies for promoting conceptual change.

Keywords: engineering education; online learning; conceptual change; misconceptions

1. Introduction

1.1 Misconceptions

There is ample evidence in the literature that students of all ages, including science and engineering undergraduates, do not easily come to understand fundamental phenomena such as heat, light, diffusion, chemical reactions, and electricity [1–3]. The difficulty in learning these concepts persists even among advanced engineering undergraduates. For example, researchers have demonstrated that undergraduate engineering students who had completed several semesters of physics courses still hold fundamental misconceptions of force and momentum [4, 5]. Similarly, Miller, Streveler and their colleagues [1, 7] have found that 25–30% of the students displayed a fundamental misunderstanding about the governing mechanisms of heat transfer and that over 50% of students' responses to questions on heat transfer were in clear violation of the 2nd law of thermodynamics. Picciarelli and colleagues [2] also found misconceptions of electricity in a sample including predominantly engineering undergraduates. Despite thousands of studies reporting student misconceptions in all areas of science and engineering [6], fundamental questions remain around why misconceptions exist and how they can be repaired. This knowledge gap is proble-

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matic since these fundamental concepts are the basis for advanced undergraduate learning in science and engineering.

1.2 Repairing misconceptions

Many studies on promoting conceptual change focus on the constructivist approach to teach science and engineering concepts [2, 7, 8]. Constructivist approaches, such as discovery learning or problem-based learning (PBL), help learners construct new meaning that builds on their prior knowledge. Through such approaches students arriving in engineering classes will continue to assimilate new knowledge into their existing knowledge making it important to help students develop the appropriate mental representations of these difficult concepts.

But what if a student's prior knowledge about a specific concept is incorrect? Since students 'typically resist giving up their pre-instructional beliefs in face of new, conflicting information data and ideas' [5, p. 1], traditional constructivist approaches might lead to more resistant misconceptions that would be resistant to subsequent traditional instruction [9].

According to Chi [9], the reason why some misconceptions are so hard to repair is that students do not have an appropriate mental representation for understanding certain complicated processes that characterize those concepts. The lack of an appropriate mental representation and a commitment to an incorrect representation make it difficult for students to process new information. For example, it would be very challenging for someone to learn the concept of 'solar system' before having many experiences (i.e., an appropriate mental representation/framework) of constituent elements such as earth, sun, planets and spaces. Robust misconceptions occur when students mis-categorize a concept —attributing it with an inappropriate 'ontology' (mental representation) because they lack the appropriate mental representation.

Thus our approach focuses on helping students develop a new mental representation or framework with ontological attributions of some particularly challenging concepts [10, 11]. By ontological attributions we mean the structural characteristics or frameworks for organizing certain processes and systems. After first establishing an appropriate ontological category, students can more easily develop a scientific view or understanding of such concepts. This approach reflects a radical switch from current practices that focus on helping students construct new knowledge to facilitating students in establishing a new alternative ontology that is consistent with the attributions of the challenging concepts [11].

1.3 Two kinds of concepts/processes

Among concepts recognized as particularly challenging and complicated, Chi [9] has identified a particular class of concepts, called *emergent processes*, which are fundamentally different from the other processes.

Emergent processes are ontological attributions or properties of a system that result from its constituent elements interacting over time in a random and simultaneous pattern, often in conjunction with eventual equilibration [9]. For example, a crowd forms a bottleneck at a door exit when a large group tries to leave at the same time. This example is the *emerging* behavior of all the individuals (i.e., elements). There are several features about this crowding process that cause it to fit the category of *emergent processes*. First, all the individuals are behaving more-or-less *the same way*. They run towards the door at about the same speed and have the same goal of exiting the door. Second, the individuals are all acting and interacting *independently* from one another: they are all trying to move forward toward the door, and in doing so, they may bump into and push each other. Third, no single individual's running or pushing another person resulted in a jam at the door and the individuals are not really pushing each other with the intention of causing the jam. The jam is caused by all the people *simultaneously* trying to run toward the door for the purpose of getting out. Their purpose was not to create a jam at the door so their interactions are not intentionally connected to the jam or crowding process. Therefore, when a crowd of people forms a bottleneck, the pattern of the crowding is due to the simultaneous effect of many elements (the individual people) interacting in similar but independent fashion (each person continuously trying to move toward the exit) and is therefore an emergent process.

To better distinguish *emergent processes* from non-emergent processes, the non-emergent processes were labeled as *sequential processes* [9]. *Sequential processes* are ontological attributions or properties of a system that result from its elements or agents of the process, acting and interacting in a causal and dependent pattern. For example, the process of building a skyscraper is the changing shape and size of the building. The agents of this process are the workers who contribute to the building and the materials they use in their construction tasks. Depending on his or her specific job or role, each worker behaves in his or her own way. It is important to note that the different aspects of the pattern are *directly caused* by a variety of different activities or interactions of the workers. The steel workers are directly responsible for making the building taller, whereas the electricians are directly responsible for installing the wiring, etc. Finally, the interactions among the different elements must often occur in a sequence. For example, the architect and engineers must first develop a blueprint for the wiring; then the electricians refer to this blueprint as they install the wiring, alongside other workers who are erecting the walls and framing of the building. Processes like building a skyscraper are *sequential processes* because various aspects of the pattern or patterns within the process (e.g., getting taller) are *directly caused* by interactions among some group of the elements (e.g., steel workers).

Many of the concepts with which engineering students struggle can be identified as *emergent processes*—including heat transfer, diffusion, and electricity. Student misconceptions of emergent process are particularly resistant to instruction because they are made at the *ontological* level—where students attribute a fundamental characteristic to the concept that is awry from the scientifically normative view [12, 9]. For example, because students are highly familiar with the ontological attributions of simple physical systems (e.g., a car driving down the street, a soccer ball being kicked), it is easier for them to interpret conductive 'heat flow' as the direct movement of a substance within a system. In fact, heat flow is an emergent process of molecules randomly colliding with other molecules and exchanging energy (one mechanism for heat transfer). Since students often do not have the *emergent process* mental representation, these types of misconceptions are robust and difficult to repair.

Slotta and Chi [13, 10] proposed that in order to help students develop the *emergent process* mental representation/framework, instruction should first identify the framework and provide students with some rich examples and properties of that emergent process. This helps students develop a 'schema' or mental representation making subsequent *emergent process* phenomena easier to understand.

1.4 Teaching difficult concepts online

Computer-based online learning offers not only the 'anywhere, anytime' access to learning materials but also capacity for flexible approaches to facilitate students' learning of difficult concepts. For example, with the Internet access, a student can study online materials at home during weekends or whenever he or she prefers, pursuing an autonomous approach to learning. More importantly, computer-based online learning has the ability to integrate well-designed instructional approaches such as simulations, which allow students to manipulate systems that are not otherwise observable or manipulable [15]. To facilitate students' development of the *emergent process* ontology, Slotta and Chi [13, 10] suggest providing them with opportunities to explore the properties of *emergent processes* associated with specific difficult phenomena, e.g., heat transfer. The latest computer technologies make such instructional approaches possible and greatly facilitate students in learning difficult phenomena.

Capitalizing on the most recent advances in computer-based online learning, we designed three computer-based online modules to promote conceptual change for undergraduate engineering students and to help them understand difficult concepts in engineering sciences. Because this is a novel approach in terms of both vehicle for teaching (i.e., self-paced online learning) and conceptual change (i.e., emergent processes), we needed to understand how the students experience the learning process and the effectiveness of the approach. The purpose of this study was to address the following two research questions:

1. What were undergraduate engineering students' perceptions of computer-based online learning embedded with simulations, video clips, interactive reflection (inquiry) prompts, and self-assessment?
2. Was such online learning, when guided by the ontological training approach of Chi and her colleagues, effective for promoting students' conceptual changes of some difficult concepts of diffusion, heat transfer and microfluidics?

To accomplish the goals of our study, we designed and developed three computer-based online learning models with integrated assessments of associated engineering concepts, and an exit online survey soliciting participants' feedback on their online learning experience.

2. Design and development of online learning modules

This study combines the work of cognitive psychologists, engineering educators, and the latest practice of integrating computer technologies to promote conceptual change in concepts where students exhibit robust misconceptions. The study expands applications of developing a new mental representation or framework with non-engineering students [10] to a population of undergraduate engineering students. We hypothesize that if we help undergraduate engineering students develop an emergent process framework we can promote conceptual change in selected thermal and transport science concepts. Moreover, having the appropriate mental representation would make it easier for students to learn a wide range of thermal and transport science concepts, subsequently, transferring this knowledge to other emergent process concepts they had not seen previously—such as microfluidics. We investigated our hypothesis using an experimental design with pre- and post-test measures of knowledge. We used three computer-based online modules titled: (1) Sequential and Emergent Processes: Part I, (2) Sequential and Emergent Processes: Part II, and (3) Nature of Science. The overall study design is depicted in Fig. 1.

Sequential and Emergent Processes: Part I was modified from Chi and Slotta's [10] original work that introduces students to *emergent processes* in order to establish that ontological framework or representation. This module was designed to foster a general understanding of the *sequential* and *emergent processes* and was intended to facilitate students' development of emergent process framework. The module introduced examples of sequential and emergent processes and described the similarities and differences between the two kinds of processes including ways to identify them. At the beginning of Part I, we included a heat transfer concepts assessment (Pre test) for checking students' prior knowledge of those concepts (Appendix A). There also was a demographic survey asking students background information at the beginning of Part I. Part I also included some instruction for diffusion and generally described diffusion in the language of emergent processes. After the instruction on diffusion, there was a diffusion concepts assessment (post test only) checking students' understanding of the concepts (Appendix B).

The Nature of Science was designed to be an equivalent module to the Sequential and Emergent Processes Part I in terms of the difficulty of content, the topic, the number of words and the use of media. It described the scientific world view, the inquiry process, and the scientific enterprise. In addition, it also included instruction on the topic of diffusion but without the general explanation of diffusion in the language of emergent processes.

Sequential and Emergent Processes: Part II introduced some fundamental concepts in heat transfer. It included some instruction on conductive heat transfer and microfluidics but without any direct discussion of the emergent nature of these processes.

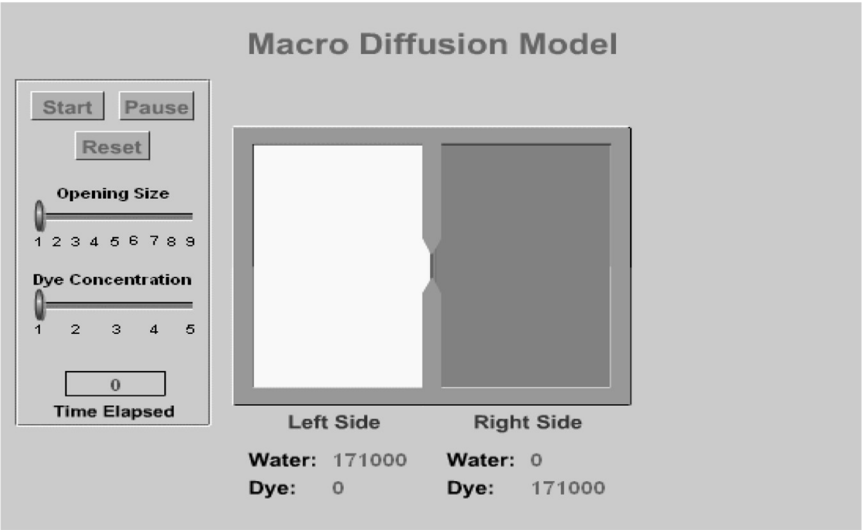
<table>
<tr><th>For Control Group</th><th>For Experimental Group</th></tr>
<tr><td><u>Nature of Science</u></td><td><u>Sequential and Emergent Processes: Part I</u></td></tr>
<tr><td colspan="2">Demographic Survey</td></tr>
<tr><td colspan="2">Heat Transfer Concepts Assessment (Pre test)</td></tr>
<tr><td>Scientific World View, etc. Instruction
(with interactive reflection prompts)
(self-assessment)</td><td>Processes Instruction
(with interactive reflection prompts)
(self-assessment)</td></tr>
<tr><td>Diffusion Instruction
<i>Not described as an emergent process</i>
(with computer simulations)
(with interactive reflection prompts)
(self-assessment)</td><td>Diffusion Instruction
<i>Generally described as an emergent process</i>
(with computer simulations)
(with interactive reflection prompts)
(self-assessment)</td></tr>
<tr><td colspan="2">Diffusion Concepts Assessment (Post test only)</td></tr>
<tr><td colspan="2"><u>Sequential & Emergent Processes: Part II</u></td></tr>
<tr><td colspan="2">Heat Transfer Instruction
(with computer simulations)
(with interactive reflection prompts)
(self-assessment)</td></tr>
<tr><td colspan="2">Heat Transfer Concepts Assessment (Post Test)</td></tr>
<tr><td colspan="2">Microfluidics Instruction (Far transfer instruction)
(with video clips)
(with interactive reflection prompts)
(self-assessment)</td></tr>
<tr><td colspan="2">Microfluidics Concepts Assessment (Post test only)</td></tr>
<tr><td colspan="2">Exit Survey(open-ended questions)</td></tr>
</table>

Fig. 1. Overview of the online learning modules.

The same heat transfer concepts assessment at the beginning of Part I was included in Part II as a post test (repeated measure) after the participants completed the instruction on heat transfer (Appendix A). We included microfluidics as a far transfer experiment of the instruction on emergent process in Part II because microfluidics principles represent an ideal application of emergent process properties as undergraduate engineering students are unfamiliar with microfluidics concepts. Therefore, it was interesting to see if there was any difference between the experimental and control groups of participants in terms of their performance on microfluidics concept assessment. A video clip that illustrates the laminar flow in microfluidics was included, along with reflective inquiry prompts about the conceptual nature of this topic. The microfluidics concepts assessment (Post test only) following the instruction of microfluidics was used to check students' understanding of those microfludics concepts (Appendix C). At the end of Part II, there was an exit survey consisting of open-ended questions that asked participants' perceptions of and feedback on their online learning experiences (Appendix D).

All three computer-based modules were hosted online using the Blackboard Open Campus, an online course management system. A variety of instructional strategies, including simulation, interactive reflection (inquiry) prompts, video clips, and embedded self-assessment were incorporated in all three modules, based on the inquiry framework of Linn and her colleagues [16]. In each module, there were two computer simulations, one at the macro level and the other at the micro level. We chose to embed simulations because they provide unique educational benefits that include opportunities to study abstract and complex physical phenomena involving many variables [17]. Simulations also provide students with the ability to see and, in a certain way, manipulate a phenomenon that is not possible with any other tools [18]. Simulations also provide an environment that approximates, simplifies, or hypothetically creates reality allowing students to change the time-scale of real processes [19]. Therefore, simulations have the ability to deliver highly motivational instruction [20].

As an example of the content of our modules, consider molecular diffusion which is an example of an emergent process that is often incorrectly described by students as a macroscopic, causal process (sequential process) based on everyday observations of diffusion. After some introductory instruction on diffusion, participants began to study diffusion using diffusion simulation (essentially a simplified version of a molecular dynamics simulation) in which groups of individual water and dye molecules randomly moved through the water and dye mixture at the macro (Fig. 2) and micro levels (Fig. 3). We used a macroscopic diffusion simulation to help participants understand the effect of variables such as dye concentration and size of diffusion opening on the rate of diffusion observed (Fig. 2). A screen shot of the simulation is shown in Fig. 2. The total number of water and dye molecules on each side of the diffusion partition is also recorded, allowing participants to understand that both water and dye molecules are diffusing. (One result of a macroscopic observation of this process is the conclusion that only dye molecules diffuse since only the dye color can be followed). In addition to the macro level simulation, we also included a micro

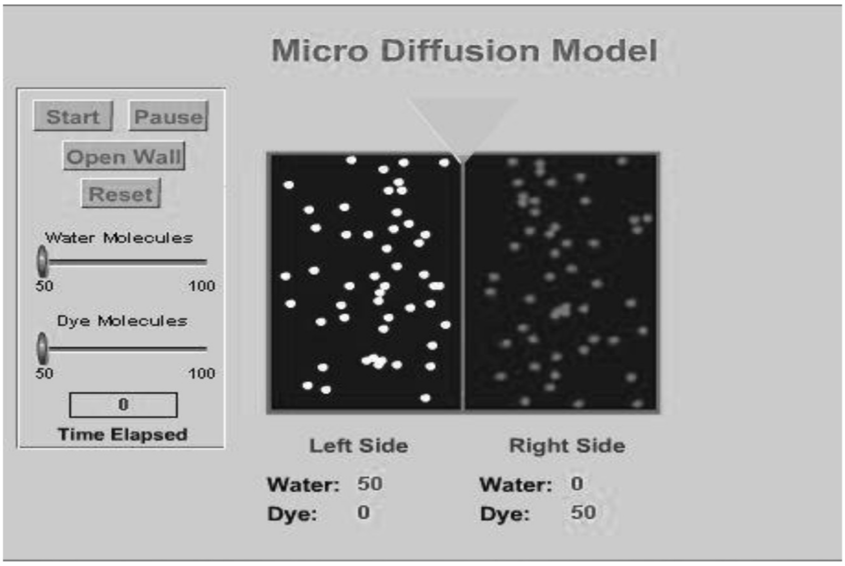


Time Elapsed: 0

Left Side — Water: 171000 Dye: 0

Right Side — Water: 0 Dye: 171000

Fig. 2. Screen shot of macroscopic water/dye diffusion simulation.



0

Water: 50
Dye: 0

Water: 0
Dye: 50

Fig. 3. Screen shot of microscopic water/dye diffusion simulation.

level simulation (essentially a simplified version of a molecular dynamics simulation) in which groups of individual water and dye molecules were studied as they randomly move through the water and dye mixture (Fig. 3). The screen shot of the microscopic diffusion simulation is shown in Fig. 3.

In both simulations, the number of water and dye molecules can be varied with user control by mouse clicking, which allows the simulations work best to achieve their purpose of enhancing the learning experience [21]. The embedded simulations allow students to manipulate some parameters that normally are not observable and this makes learning more interesting to the students [1, 15]. The simulations could also provide students with an opportunity to dual code the information [22] and generate a cueing effect that enhances learning by means of linking visual cues and/or images in a simulation to their corresponding text of instruction, meeting a multi-sensory learning preference [23].

Because reflection is an important part of the learning process in terms of mastering content and being a self-regulated learner [24, 25], all three online modules were embedded with interactive reflection and inquiry prompts that asked the students to reflect on their learning and describe in their own words about the learning materials or phenomena. For example, for the diffusion simulation, we tried to use prompts to elicit written descriptions of how and why diffusion occurs as students construct an emergent process understanding of the diffusion phenomenon. Students were prompted to describe observed behavior by answering reflective 'inquiry prompts' such as:

- Do all of the water and dye molecules behave and interact in more or less the same way?
- Can the water and dye molecules interact with any other water and dye molecules in an unrestricted way?
- Can all the water and dye molecules bounce around and collide with each other at the same time?

In our study, there was no feedback given to the students regarding their answers to these prompts. The prompts were designed to engage student reasoning and reflection during their progress through the online modules, and were inserted at strategic points where we think it is important for the students to understand the content [16]. For example, students were often prompted to reflect on, and explain an important part of the text that he or she may not have completely understood, which enhanced students understanding of the online modules [10].

In addition to simulations and interactive reflection prompts, all three online modules contained text, graphics, and self- assessments to facilitate students' learning. The self-assessment questions were labeled either as 'What do you think?' or 'Further reflection' and usually placed at the end of discussing a particular concept. All self-assessment questions asked students' written responses and had the same functions as those of interactive inquiry prompts described previously. During the design and development of the computer-based online modules, we pilot-studied all three modules with undergraduate engineering students and had numerous rounds of expert reviews. Subsequent revisions of the modules were made according to the results of the pilot study and expert reviews. The computer-based online modules were implemented and evaluated at a Midwest research university in the U.S.

3. Research design

All three computer-based online modules were hosted in the Blackboard Open Campus, which not only provides the affordance of computer-based online learning but also provides researchers and participants with easy access from multiple locations. In addition, researchers can easily retrieve participants' responses to different assessment questions and track their participation activities.

To achieve the objective of the study, we adopted a mixed research methods design in terms of using both qualitative and quantitative approaches to answer different research questions [26, 27]. The mixed research methods design allows the collection of both qualitative and quantitative data in the same study. The qualitative method was used to collect participants' written responses to a post-survey (exit survey) and to answer the first research question about participants' experiences of learning the modules online. The survey included open-ended questions asking participants' perceptions of and feedback on the online learning. The quantitative method was used to answer the second research question relating to the effectiveness of the online learning modules and consisted of an experimental study (Fig. 1).

3.1 Validity and reliability of the instruments

To ensure the face validity of the exit survey, survey questions were pilot tested by another group of undergraduate engineering students with similar background for issues regarding relevance, appropriateness, grammar, clarity, and potential redundancy [28]. (Sample questions are shown in Appendix D).

All concepts assessment questions about diffusion, heat transfer and microfluidics were reviewed independently by three researchers and pilot tested prior to the study. (Sample questions are shown in Appendix A, B, and C). The heat transfer assessment questions were chosen from the Thermal and Transport Concept Inventory (TTCI) for identifying students' misconceptions [29] and administered as pre and post tests to both control and experimental groups of participants. The reliability coefficient computed by Cronbach's alpha estimates of internal consistency of heat transfer concepts assessment was 0.77, which is considered acceptable in education research.

3.2 Data collection

One of our researchers met with all participation volunteers prior to the study. The researcher explained the purpose of the study, confirmed the participation eligibility (major in engineering, number of course taken in specific subject areas, etc.) of all participants, demonstrated how to access the online learning modules, and had the study content forms signed. The participants were typical undergraduate engineering students in terms of their age range (from 18 to early 20s). All participants were juniors or seniors majoring in mechanical, chemical, or materials engineering, who had taken at least two courses in diffusion, heat transfer or fluid dynamics. Through an experimental design as shown in Fig. 1, all participants completed the study (each participant studied two modules) on their own. The experimental group received Sequential and Emergent Processes: Part I while the control group received a more generic module called Nature of Science. Both groups took the Sequential and Emergent Processes: Part II. All participants had studied the macro and micro levels simulations on water and dye diffusion. Most participants had not taken any credited course delivered online through a computer. Thus, the training modules were most likely their first learning experience with computer-based online learning.

We administered an exit survey to all the participants (N = 60) who were randomly assigned into an experimental group (n = 30) and a control group (n = 30). The exit survey with 60 engineering undergraduates was used to capture participants' experiences of the online learning. Using the open-ended questions, all participants were asked to describe their perceptions of and feedback on their learning experiences of computer-based online modules in writing. At the end of the study, the same researcher again met all participants individually and asked every participant to verbally describe his or her overall impression of the learning process.

To assess the effectiveness of the computer-based online training modules (research question 2), we required all participants (N = 60) to complete the study on two consecutive days (one module per day) in a total of approximate four to five hours (Fig. 1). The experimental group completed the Emergent and Sequential Processes Part I and Part II modules, and the control group completed the Nature of Science and Emergent and Sequential Processes Part II modules. Both groups received the same instruction on the subject of diffusion, heat transfer, and microfluidics. However, the experimental group was also given the instruction on emergent and sequential processes (Fig. 1). In addition, the participants in the experimental group had a different section of instruction on diffusion, which introduced diffusion in the language of emergent processes and described diffusion in general as an emergent process (Fig. 1). The microfluidics instruction and assessment were included as a far learning transfer part, which all participants had to complete.

4. Results

The first part of the results related to the first research question was the undergraduate engineering students' perceptions of and feedback on their learning the modules online. The second part of the results related to the second research question was whether the online modules were effective based on the experimental study.

4.1 Students' perceptions of and feedback on computer-based online learning

To answer our first research question: *What were undergraduate engineering students' perceptions of computer-based online training modules embedded with simulations, video clips, interactive reflection (inquiry) prompts, and self-assessment*?, we analyzed and coded the qualitative data collected from the exit survey. Codes for categorizing students' responses to all open-ended questions were generated through a combination of inductive and deductive approach [30]. First the researchers created an initial coding scheme based on both the open-ended questions and their initial impression of reading through five participants' responses to all the survey questions. Then the researchers used the initial coding schemes to code all students' responses. Additional codes emerged from the data that were not captured by the initial coding scheme process were added which was referred to as the inductive approach [30].

4.1.1 Perceived advantages of computer-based online learning

The following themes/patterns were developed after analyzing and coding all the participants' responses to the open-ended survey questions: (1) *perceived advantages of computer-based online learning*, and (2) *perceived advantages of a mixed (face-to-face and online) instructional approach*. For the perceived advantages, there are also several sub-themes: (1) *the right pace or self-paced learning and having the ability to go fast or to slow down*; (2) *being flexible and suitable for multiple learning styles; and* (3) *more hands-on activities and more interaction with the content.*

When asked about the advantages of computer and self-paced online learning, all sixty participants seemed to have favorable attitude for online learning and listed detailed advantages of such online learning approach. Specifically, 42 out of the 60 participants responded that being able to go through the learning modules at his/her pace as the main advantage of computer-based online learning, which was consistent with previous research on online learning [31]. For example, one student wrote '*You have some time to pause and reread difficult concepts* [*during computer-based online learning*].' Another student wrote: '*Students can repeat modules and take a longer amount of time on sections that they don't quite understand. They can also spend more time experimenting with the simulations that would otherwise be left unexplored in [face-to-face] clas*s.' This demonstrates that computer-based online learning allowed students to learn at their own comfortable pace and had the ability to present difficult content over and over again. The right pace of computer-based online learning is also critical in facilitating students understanding and conceptual changes of misconceptions [10]. Since in lectures, instructors often have to move too quickly to meet the time constraints of a large engineering or science class and have insufficient time explaining or exploring some difficult concepts in depth. One good summary of the advantage of self-paced computer-based online learning was best reflected by one student's response: *'The biggest advantage [of computer-based online learning approach] is the self (–) paced approach, it would be very hard to get lost or in over your head when doing it at your own pace*'. Thus, computer-based online learning not only provided students a right pace to work through the learning materials but also contributed to effective learning of difficult concepts.

Twenty-two out of the 60 participants responded that computer-based online learning provided them a very *flexible and convenient* approach to learning and it was also *suitable for* multip*le learning styles (i.e., best time to learn and better suits a 'quick' or 'slow' learner).* For example, one student wrote '[Online] *Courses like this give you more flexibility in scheduling since you can work on them anytime of the day.*' Another student wrote '*There is no class that must be attended [for an online course], so topics can be learned when the student is ready to learn, not, for example, very early in the morning when they are still tired.*' Providing a flexible learning approach also entails a less threatening learning environment for some students. For example, if a student prefers studying on his/her own time so that he/she can better concentrate on the difficult concept without feeling the pressure of his/her peers from sitting in a classroom. As one student wrote: '*They [Computer-based online learning modules] are good for students who learn at different rates*' and '*. . . in a classroom it is unrealistic to think that everyone is learning at the same pace. . . .students can learn at their own [time] and not feel pressured in class*'. Thus, computer-based online learning allowed participants a flexible schedule as when and where to learn and most importantly a less threatening learning environment to learn difficult concepts.

Eleven out of the 60 participants considered that computer-based online learning provided them *more hands-on activities and more interaction with the content.* For example, one student wrote '*They [computer-based online learning] provide a much more interactive approach than just taking notes from a professor*. . . .' and '*These approaches are hands on and engaging*.' Similarly, another student wrote '*You can revisit material if you didn't completely get it the first time. You can interact [with the materials] more than in a large engineering class. You can experiment with [simulation] models as you learn the concepts*.' In addition, another student wrote '*The advantages [of a computer-based online learning approach] are that you can make an interface that a student can interact with giving a more tangible idea of the concept being taught. In addition students can move at different paces to avoid boredom with material.'* Due to the abilities of providing hands-on activities such as manipulative simulations and multiple ways (e.g., words, pictures, simulation) of presenting the same concept, computer-based online learning can actively engage students and enhance the learning of difficult concepts [15]. The following table briefly summarizes the perceived main advantages of computer-based online learning.

4.1.2 Perceived advantages of a mixed (face-to-face and online) instructional approach

However, when asked about which of the three learning approaches: self-paced online learning, a face-to-face learning, and a mixed of face-to-face and self-paced online learning, they would prefer if given the options, 41 out of the 60 participants would prefer a mixed of face-to-face and online learning approach. Only five participants selected computer-based online learning and 15 participants selected instructor-led classroom instruction. All participants also explained why they preferred a specific learning approach. Most of the participants preferred a mixed approach because such approach offers the advantages of both computer-based online learning and face-to-face instructor-led instruction. This is consistent with the previous finding that 42 out of 60 participants were favorable of self-paced learning—the main advantage of online learning. For specific perceived advantages of the mixed approach, two main themes/patterns emerged: (1) the nice feature of self-paced learning plus the immediate clarifications of an instructor; and (2) the opportunity to learn from a computer and a professor.

While enjoying the opportunity of learning the content on their own at their own pace, most students (41/60) would prefer the immediate clarifications and explanations offered by an instructor during a learning process. For example, one student wrote: *'Meeting in class doesn't always allow me to learn at the pace I want whereas only doing computer simulations [computer-based online learning] does not allow for questioning and discussion. And the mixed approach would allow both. . .'* This finding calls for more embedded human interactions in online course design instead of merely providing the content and letting the students learn on their own. A short recorded video showing the instructor's explanations of some anticipated issues related to a difficult concept could help to achieve the above purpose, adding some personal touch to an online course.

Similarly, other students would prefer the mixed approach because it offers the opportunity to learn both from a computer and an instructor. For example, like one student put '*I feel that a mixed approach is always best because you get more than one perspective [way of explanations] and you are able to interact with others that might be able to explain something you don't fully understand [from the computer].'*

4.2 Effectiveness of the computer-based online learning modules

To answer our second research question and assess the effectiveness of the computer-based online learning in promoting conceptual change, we analyzed the quantitative data from the concepts assessment of heat transfer, diffusion and microfluidics. Table 2 displays the information related to the number of correct responses by group for the three concepts assessments.

Results of the effectiveness of the online modules for promoting students' conceptual changes were mixed, which were published in a previous study [29]. For diffusion, the overall mean for the experimental group (15.40) was larger than that (13.87) of the control group (Table 2). In addition, there was a

Table 1. Perceived Main Advantages of Computer-Based Online Learning

Perceived Main Advantages	**Percent of Responses**
Has the right pace or self-paced learning and the ability to go fast or to slow down during the learning.	70%
Provides a very flexible and convenient approach to learning and accommodates for multiple learning styles.	37%
Provides more hands-on activities and more interaction with the content.	18%

Table 2. Number of Correct Responses for each Concept Assessment by Group

	Mean (# of correct responses)		**Standard Division**		
Subject	**Experimental Group (EG)**	**Control Group (CG)**	**Experimental Group (EG)**	**Control Group (CG)**	**p-value (EG & CG)**
Diffusion	15.40	13.87	2.673	2.886	0.037
Microfluidics	3.60	2.77	1.380	1.455	0.027
	Mean (pre & post)		**Standard Division**		
	Experimental Group (EG)	**Control Group (CG)**	**Experimental Group (EG)**	**Control Group (CG)**	**p-value (pre & post)**
Heat transfer Pre	14.63	14.03	5.0669	5.616	0.823
Heat transfer Post	16.60	15.93	6.239	6.243	

significant difference (p = 0.037) between the two groups with a moderate gain (d = 0.56) in terms of post test mean scores for the experimental group. This showed that the online learning module did help those engineering students in the experimental group with their understanding of some diffusion concepts. For heat transfer, the overall mean gain (the average of post test scores minus pre test scores) for the experimental group (1.10) was larger than that (0.97) of the control group (Table 2). However, there was no significant difference between the two groups in terms of mean gains (p = 0.823). The non-significant statistic showed that the online learning module did not help those engineering students better understand the heat transfer concepts in the assessment questions. For microfluidics, the overall mean for the experimental group (3.60) was larger than that (2.77) of the control group, which was a significant difference (p = 0.027) with a moderate gain (d = 0.60) for the experimental group. This showed that the online learning module did help those engineering students in the experimental group with their understanding of some fluid mechanics concepts. The results of the effectiveness of the online modules presented above were from the first round of the study. Additional similar data were collected after we revised some of the concepts assessment questions and await for further analysis.

5. Discussion

According to the survey results, it is clear that computer-based online learning has a long way to go before it would replace an instructor, because of the breadth and depth of human interaction that occurs during the teaching and learning process. However, computer-based online learning that offsets the lack of hands-on activities and time constraints of a large engineering lecture has been shown here to benefit students—particularly with regard to addressing some difficult but key engineering concepts. Thus, a mixed approach of instructor-led and computer-based online learning may offer the best means for learning difficult concepts, and help respond to variations in students' approaches to learning.

The non-significant outcomes between the control and experimental groups, in terms of the heat transfer concept assessment warrant further investigation as there are several possible factors that might have contributed to this result. First, the concept assessment questions on heat transfer might not accurately measure students' understanding of those concepts. Second, most participants had already taken several courses in heat transfer or related topics over several semesters prior to this study. The prior instruction may have included approaches and experiences that served to reinforce students' misconceptions [32]. Different data analysis approaches, perhaps incorporating the number of courses taken, may serve to refine these outcomes and shed light on mediating factors [33]. Third, further data analysis of students' written responses to the multiple assessment questions, such as looking at the kind of language of different processes, may shed more light on this research [33].

The use of computer-based learning has dramatically increased throughout the world in recent years. In the United States, there were 5.6 million college students enrolled in at least one online course by fall 2010 [34]. The computer-based online learning modules from this study could enable students to interact with simulations, reflect on their own ideas, and engage with challenging scenarios. By integrating such elements into their courses, instructors could find new ways to address some notoriously difficult concepts and phenomena. As we move into the 21st century, technological advances are being made at the microscopic, molecular, and atomic levels in many fields of engineering (e.g. microfluidics, biotechnology, genetic engineering, microelectronics, nanoscale machines, molecular computers) that challenge engineering education to respond to these evolving disciplines.

However, engineering has the fewest online courses and online programs, compared with other disciplines [35], which may not be due to the feasibility of the subject (i.e., for online learning) but rather to the lack of effective design principles for online courses in engineering. What the engineering learning community needs is effective and flexible online course/modules with multiple ways to achieve interactions between students and instructors. The development of computer-based online modules, such as those described here and developed by researchers at MIT [14, 15], may become an important part of engineering education. Through the use of computer-based modules, we can enhance our courses, allowing students to explore the interactions and concentrate on conceptual understanding of the phenomena.

This study has some limitations primarily associated with the sample population. First, the participants of this study were from a single top engineering school. Generalizability may therefore be limited. In particular, the competitive nature associated with being a top school may have favorably skewed the findings in terms of their motivation to learn through computer-based online learning modules. Moreover, different or additional coding categories might emerge in the qualitative portion of the study if diversity in school contexts were increased. Second, the results of the effectiveness of the online learning modules presented in this study were from the first round of the data collection, which may limit the generalizations of the study. Additional similar data have been collected from studies underway at other institutes after we revised some of the concepts assessment questions. These data await further analysis.

6. Conclusions

According to the exit survey, most of the participants considered the main advantages of computer-based online learning to be the ability to self-pace and the flexibility of schedule. For online modules, students can go fast or slow down and revisit some materials at their convenient or most productive time without being rushed during the learning process. The disadvantages of these online modules were the lack of immediate clarifications from an instructor and human interaction. Thus most participants would prefer a mixed approach of face-to-face and online instruction in order to reap the benefits of both learning approaches. The survey results also showed that most of the students were favorable for learning and studying engineering and science through computer-based online learning approach. According to the concepts assessment of diffusion and microfluidics, such online learning modules embedded with simulations, self-assessment, reflective inquiry prompts, and video did help the engineering students with their understanding of some difficult concepts. This was the first study that provided a discipline-based example in engineering education for how to use computer-based online learning and emergent properties of complex systems to help undergraduate engineering students learn some difficult concepts. It draws upon the most contemporary psychological and pedagogical theories as foundations for the conception and design of computer-based online learning environments. Thus, it provides engineering educators some pedagogical ideas and examples to effectively integrate and adopt computer-based online learning within engineering education.

Based on this study, there are several directions that are worth pursuing. First, research on online pedagogy in engineering, i.e., how to teach and learn engineering online and how to design interactive and effective online courses in engineering are needed. Second, describing complex and difficult science and engineering concepts in the language of emergent processes are encouraged. Third, researching how to *prevent* robust and persistent misconceptions of difficult science and engineering concepts that may be reinforced during formal instruction instead of repairing and correcting those misconceptions would be fruitful.

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Appendix A

Sample Heat Transfer Questions

Suppose you have 2 beakers collected by a short tube with a clamp. Beaker #1 contains hot water and Beaker #2 contains cold water. Each beaker contains the same amount of water. Thus there is a temperature difference between the two beakers but no water will flow between the beakers since the water levels are the same. At first the tube is clamped shut so nothing happens in the two beakers. When the clamp is removed, a thermometer is each beaker shows that Beaker #1 temperature decreases and Beaker #2 temperature increases.

Q1. Why does the hot beaker cool down and the cold beaker heat up? {open-ended response}

Q2. How do the hot water molecules spread out from Beaker #1?
  (a) By the hot molecules being forced to move from an area of high thermal concentration (the hot end of the tube near Beaker #1) to an area of lower thermal concentration (the cold end of the tube near Beaker #2).
  (b) Because of the temperature gradient from one end of the tube to the other end.
  (c) By spreading out where there is more room in the colder water for hot molecules.
  (d) By all the molecules colliding with each other, and purely by chance, the hot molecules move through the tube and also exchange energy with other molecules. {correct}

Q3. As energy seems to flow from Beaker #1 to Beaker #2, is it possible for a ‘hot’ molecule in Beaker #2 to move backwards to Beaker #1?

(a) No, once a molecule has moved to Beaker #2 from an area of higher thermal concentration to lower thermal concentration, it can never go back.
(b) Yes, the hot molecules need to create equilibrium and so one of more of them needs to go back to Beaker #1 to maintain a balance.
(c) Yes, all molecules move around randomly and can collide with each other, and any molecule (hot or cold) can go anywhere between beakers. {correct}
(d) No, the hot and cold molecules are linked together and the movement of one affects the movement of the other. So a hot molecule cannot just move back to Beaker #1 by itself.

Appendix B

Sample Diffusion Questions

A beaker is filled with 40 ml of water and 1 spoonful of sugar. A balloon is filled with 5 ml of water and 2 spoonfuls of sugar. The walls of the balloon are equally permeable for sugar and water molecules (this means that both sugar and water molecules can pass through the walls of the balloon).

Q1. Assuming the sweetness of the water in the beaker increases when the balloon is complete submerged in the water in the beaker. How will this occur?

(a) Random motion of sugar molecules will result in some sugar molecules moving from the balloon to the beaker; when the number of sugar molecules increases, the sweetness in the beaker will increase.
(b) Collectively, the random motion of water and sugar molecules results in the proportion (concentration) of sugar molecules increasing in the beaker and the proportion (concentration) of water molecules increasing in the balloon. {correct}
(c) Random motion of water molecules will result in some water molecules moving from the beaker to the balloon; when the number of water molecules decreases, the sweetness in the beaker will increase.
(d) Since both water and sugar molecules move randomly, no change in water sweetness will be observed in the beaker.

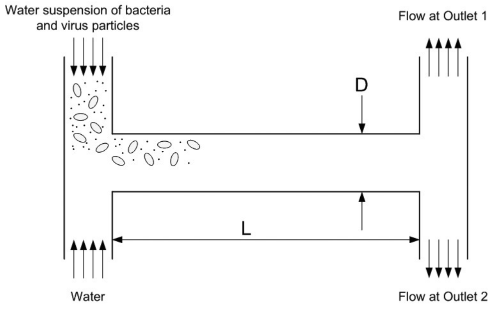
Q2. Based on your answer to the question above, how do the sugar and water molecules move in the ways you described?

(a) Both sugar and water molecules move randomly no matter what other molecules are in the vicinity—collectively, the pattern of movement from high concentration to low concentration emerges from this random motion. {correct}
(b) Each type of molecule wants to move away from similar molecules—sugar molecules moving away from other sugar molecules and water molecules moving away from other water molecules.
(c) Each type of molecule moves directly along its concentration gradient from high concentration to low concentration without interacting with other types of molecules
(d) Each type of molecule is attracted to molecules of a different type—sugar molecules want to be surrounded by water molecules and water molecules want to surround sugar molecules.

Appendix C

Sample Microfluidics Questions

Q1. As shown below, a water suspension of bacteria (large) and virus (small) particles and a pure water stream are introduced into a microfluidic device. Each stream flowrate is the same and the combined flow is from left to right. The length of the channel (L) is about 100 times larger than the diameter (D).



If the combined suspension/water flowrate in the device is always laminar, what species (e.g. bacteria, virus) would we expect to detect at outlet stream 1 and at outlet stream 2?

(a) Virus and bacteria particles at outlet 1; only water at outlet 2
(b) Virus and bacteria particles at both outlets
(c) Virus and bacteria particles at outlet 2; only water at outlet 1
(d) Virus and bacteria particles at outlet 1; virus particles at outlet 2
(e) Virus and bacteria particles at outlet 1; bacteria particles at outlet 2

Q2. Why do the virus and/or bacteria particles end up in the outlets you predicted? {open-ended response}

Q3. How do the virus particles spread out in the flow?

(a) By the virus particles being forced to move from an area of higher concentration to an area of lower concentration.
(b) By spreading out where there is more room in the water, which initially has no concentration of virus particles.
(c) Because of the concentration gradient of virus particles.
(d) By all of the virus particles, bacteria particles, and water molecules colliding with each other, and purely by chance, the virus particles move throughout the water. {correct}

Appendix D

Sample Post Survey Questions

Q1. What are the advantages of a computer-based and self-paced learning approach for modules or courses like these?

Q2. Which learning approach would you prefer based on your experience with the two modules?

(a) A computer-based and self-paced learning approach like the way I went through the two modules.
(b) An instructor teaching the two modules to a group of students (including me) in a classroom during a certain time
(c) A mixed approach of computer-based and self-paced learning with some instructor's face-to-face teaching the same modules in a classroom

Please explain why you prefer a specific learning approach?

Q3. Would you think some subject areas are better for a computer-based and self-paced learning approach than other subject areas? Why?

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