AC 2010-1826: REPAIRING STUDENT MISCONCEPTIONS USING ONTOLOGY TRAINING: A STUDY WITH JUNIOR AND SENIOR UNDERGRADUATE ENGINEERING STUDENTS

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Repairing Student Misconceptions Using Ontology Training: A Study with Junior and Senior Undergraduate Engineering Students

Abstract

Previous studies reported that misconceptions related to heat transfer, fluid mechanics, and thermodynamics, persist among engineering juniors and seniors even after they have completed college-level courses in the subjects. This study focuses on developing methods to repair some particularly robust misconceptions in diffusion, heat transfer, and microfluidics. Three online training modules were created in Blackboard that provided instruction about two distinct scientific processes (sequential and emergent processes), heat transfer, diffusion and microfluidics. An experimental study with 60 juniors and seniors undergraduate engineering students was conducted at a large Midwestern US university. Experimental and control cohorts completed the on-line multimedia modules including macroscopic and microscopic simulations of heat transfer and diffusion processes. Quantitative data were collected through multiple-choice questions assessing conceptual knowledge of diffusion, heat transfer, and microfluidics. In addition, qualitative data were collected through participants' verbal explanations of their multiple choice answers. Both quantitative and qualitative results indicate that there was statistically significant improvement in the experimental cohort compared to the control cohort in conceptual understanding of diffusion and microfluidics processes but there was no significant improvement in heat transfer. This result might be attributed to a "pedagogical learning impediment" associated with participants having taken prior heat transfer courses or which assessment questions which did not adequately probe for conceptual understanding of heat transfer.

Introduction

Previous studies reported that misconceptions related to heat transfer, fluid mechanics, and thermodynamics, persist among engineering juniors and seniors even after they have completed college-level courses in the subjects. [1] Slotta and Chi [2, 3] have demonstrated that, with middle school and non-science college students, misconceptions can be repaired after training students in appropriate mental frameworks or schemas for some difficult concepts. This innovative instructional approach- ontological schema training method - focuses on facilitating students' conceptual change by helping students develop appropriate schemas or conceptual frameworks for learning difficult science concepts.

The ontological schema training approach consists of two distinct categories of concepts, sequential processes and emergent processes. The sequential process results when interaction agents in a *causal and dependent* pattern causes some "outcome in a sequential and dependent" way. [2] Main properties of sequential processes in terms of the pattern of the outcome are: causal and intentional agents, sequential and dependent, differentiated behavior or actions. For example, the pattern of 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. Each worker behaves in their own way, depending on his or her specific job or role. 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, and etc. Finally, the interactions among the different elements must often occur in a sequence. For example, the architect must first lay out 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 can be called *sequential processes*, because various aspects of the pattern or patterns within the process are *directly caused* by interactions among some group of the elements (workers). In this example, when the building gets taller, it was directly caused by what the steel workers did.

However, an emergent process has its constituent elements interacting over time in a *random and simultaneous* pattern. Furthermore, interactions among and between its constituent elements "result from the collective and simultaneous interactions". [2] The main properties of emergent processes in terms of the pattern of the outcome are: undifferentiated or uniform interactions, simultaneous and random interactions, and unidentified causes of behavior. For example, a crowd forms a bottleneck at a door exit. The pattern of this example is the *emerging* behavior of all the elements or individuals. There are several features about this crowding process. 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 just exiting the door. Second, the individuals are all acting and interacting independently of one another simultaneously: they are all just 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 aren't 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. Fourth, all the people want to do is run to the door to get out. They were not planning to create a jam at the door, or their interactions are not necessarily directly connected to the jam or crowding process (pattern). When a crowd of people forms a bottleneck, the pattern 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). The pattern emerges as a result of all the elements interacting in this fashion.

Many of the concepts with which engineering students struggle can be identified as emergent processes such as heat transfer, diffusion and electricity. [4] Emergent processes misconceptions are particularly resistant to traditional instruction because they are made at the ontological level – where students ascribe a fundamental characteristic to the concept that is at odds with the scientifically normative view. [4, 6] In order to help students learn concepts of the Emerging Process ontology, instruction should first identify the ontology and provide them with some rich examples and properties of that ontology. [3,7] This will help students develop a "schema" or mental framework for that ontology that would make subsequent concepts easier to understand. Referred to as "schema training framework," this instructional approach has been successful with both middle school students and undergraduate psychology students in repairing their misconceptions of science concepts. [2, 3] For example, schema training designed to help students develop a correct mental model for molecular diffusion includes text and graphics describing molecular diffusion as an emergent process, macroscopic and microscopic computer simulations that students can manipulate to observe the effects of diffusion at different length scales, prompt questions to promote self-refection, and quantitative and qualitative concept questions to measure understanding.

Would this same approach work with engineering students? To answer this question, we designed two online schema training modules based on Slotta and Chi's work.[2, 4, 5] The modules were designed to help engineering students develop the appropriate schemas they need to understand key concepts in heat transfer, diffusion, and microfluidics. We then examined the effectiveness of the training modules. Because the training modules were designed for facilitating students' conceptual change by helping them develop appropriate schemas or conceptual frameworks for learning difficult engineering concepts specific research questions were:

1. How effective did the schema training modules help engineering students develop the appropriate schemas for learning difficult key engineering concepts in a. diffusion; b. heat transfer; and c. microfluidics?

2. How effective did the schema training modules facilitate students' conceptual change in terms of the kind of emergent process language they displaced?

Research Design

An experimental study with 60 junior or senior engineering students was conducted at a large Midwestern US research university. The participants were chosen from a pool of volunteers according to the number of courses taken in thermodynamics, heat transfer and/or fluid dynamics. We selected those students who had taken more than one course in the above three areas because we wanted to identify and repair their misconceptions of some difficult concepts of those subjects. After the participants were selected, they were randomly assigned to either the experimental or control group for a two-day study. On day one, as shown in Figure 1, a pre-test in heat transfer concepts was used as a further measure of the "equivalence" of the two groups at the beginning of the study. A pre-test heat transfer question is shown in Appendix A.

Then the experimental group completed a training module describing the characteristics of two kinds of processes (sequential and emergent processes) which was intended to facilitate students' conceptual change. The training module for the experimental group also described diffusion as an emergent process, to help them develop a schema for thinking about diffusion in emergent terms. The control group completed an approximately equivalent module that described the nature of science. Diffusion is described but no mention is made of emergent processes. Both groups also completed the same test on diffusion concepts. A sample microfluidics question is shown in Appendix A.

Procedure	Experimental Group	Control Group
Pre-Test	Heat transfer concept questions	
Training Module	Sequential and Emergent Processes (with reflection prompts); Diffusion as an example of an emergent process (with reflection prompts)	The Nature of Science (with reflection prompts); Diffusion example with **no** mention of emergent processes (with reflection prompts)
Test for Understanding	Diffusion concept questions (requiring verbal explanations for multiple choice questions)	
Target Instruction Module	Heat transfer instruction (with reflection prompts)	Heat transfer instruction (with reflection prompts)
Post-Test (Repeated Measure)	Heat transfer concept questions	
Far Transfer Instruction	Microfluidics	
Test for Far Transfer	Microfluidics concept questions (requiring verbal explanations for multiple choice questions)	

Figure 1. Research Design and Data Collection

On the following day (day two), both groups completed the same instruction on heat transfer principles. Post-test concept questions on heat transfer were answered by both groups. Finally, both groups completed the same instruction on microfluidics - a far transfer experiment. We chose microfluidics as the field of instruction and concept assessment for two reasons. First, microfluidics principles represent an ideal application of emergent process principles. And secondly, undergraduate engineering students were unfamiliar with this subject and so were naïve about the content. A sample microfluidics concept question is shown in Appendix A.

Most importantly, verbal explanations for multiple choice questions on diffusion and microfluidics concept assessment were also collected from both groups of participants. The collection and analysis of these qualitative data allowed us to further examine the effectiveness of the schema training modules and to determine whether the schema training modules helped the participants develop conceptual changes of these difficult diffusion and microfluidics concepts.

Data Analysis and Results

Quantitative Results

For the first research question: *How effective did the schema training modules help engineering students develop the appropriate schemas for learning difficult science concepts - key concepts in a. diffusion, b. heat transfer, and c. microfluidics*?, we analyzed the quantitative data from the multiple choice questions for heat transfer, diffusion and microfluidics. The following presents the quantitative results.

Diffusion Quantitative Results

Both groups of participants took the test on diffusion concepts on the first of the study. Based on the data from 19 multiple choices questions on diffusion, the overall mean for the experimental group (15.40) was larger than that (13.87) of the control group (see Table 1). In addition, there was a significant difference (p=.037) between the two groups. This showed that the schema training approach did help those engineering students in the experimental group with their understanding of some diffusion concepts.

Table 1- Descriptive Statistics for Students' Performance on Diffusion

Group	N	Mean Gain	Std
Experimental	30	15.40	2.673
Control	30	13.87	2.886

Heat Transfer Quantitative Results

Both groups of participants (experimental and control) had taken the pre test for heat transfer at the beginning of the study on the first day. Both groups had taken the post test for heat transfer on the following day. The pre and post tests consisted of 18 multiple choice questions which were chosen from the Thermal and Transport Concept Inventory (TTCI) for identifying student misconceptions. [8]

Based on the pre and post tests, the overall mean gain (the average of post test scores minus pre test scores) for the experimental group (1.10) was larger than that (.97) of the control group (see Table 2). However, there was no significant difference (p=.823) between the two groups in terms of mean gains. The non-significant statistic showed that the schema training approach did not help those engineering students in repairing their misconceptions with concepts in heat transfer.

Table 2- Descriptive Statistics for Mean Gain on Heat Transfer

Group	N	Mean Gain	Std
Experimental	30	1.10	1.972
Control	30	0.97	2.591

Microfluidics Quantitative Results

Both groups of participants took the microfluidics test on the following day (day two) of the study. Based on the data from 5 multiple choices questions on microfluidics, the overall mean for the experimental group (3.60) was larger than that (2.77) of the control group (see Table 3). In addition, there was a significant difference (p=.027) between the two groups. This showed that the schema training approach did help those engineering students in the experimental group with their understanding of some fluid mechanics concepts.

Table 3- Descriptive Statistics for Students' Performance on Microfluidics

Group	N	Mean Gain	Std
Experimental	30	3.60	1.380
Control	30	2.77	1.455

Qualitative Results

To answer the second research question: *How effective did the schema training modules facilitate students' conceptual change in terms of the kind of emergent process language they displayed?*, we analyzed the qualitative data from the verbal explanation questions for diffusion and microfluidics. Our qualitative data analysis consisted of coding students' verbal explanations for their answers to the multiple choice questions on diffusion and microlfuidics. This was done because we found a significant difference between both groups of participants (control and experimental) for these two subject area. As for the heat transfer, since there was no significant difference found between the experimental and control groups, we did not further examine the qualitative data collected from heat transfer.

Before starting to code the qualitative data, we developed a coding schema that contains specific characteristics of both emergent and sequential process languages. Prior to the coding, three researchers coded the same set of data selected from three verbal explanation questions on diffusion for 10 participants and the inter-coder agreement was over 90%. Then two researchers independently coded all the two sets of data collected from diffusion and microfluidics. If emergent process language, such as the participant's explanation has one or more attributes of

Emergent Processes, e.g., a clear description of some process that is being driven toward equilibrium; or a detailed description about the behaviors of a single "element" (molecule, etc) and how it is independent, that participant's response was coded as 1, otherwise it was coded as 0. After the coding, we summed all the "1"s and "0"s for both groups of participants and conducted a nonparametric two independent samples test between the experimental and control groups because a nonparametric test makes minimal assumptions about the underlying distribution of the data. [9] The following section presents qualitative results.

Diffusion Qualitative Results

Based on the 22 verbal explanation questions on diffusion, the overall mean for the experimental group (17.03) was much larger than that (2.97) of the control group (see Table 4). In addition, there was a significant difference ($p<0.000$) between the two groups. This showed that the schema training approach did facilitate students' conceptual change in terms of the kind of emergent process language they displayed when explaining their answers on the multiple choice questions on diffusion concepts.

Table 4- Descriptive Statistics for Students' Verbal Explanations on Diffusion

Group	N	Mean Gain	Std
Experimental	30	17.03	2.125
Control	30	2.97	1.847

Microfluidics Qualitative Results

Based on the 6 verbal explanation questions on microfluidics, the overall mean for the experimental group (4.10) was much larger than that (.63) of the control group (see Table 5). In addition, there was a significant difference ($p<0.000$) between the two groups. This showed that the schema training approach did facilitate students' conceptual change in terms of the kind of emergent process language they displayed when explaining their answers on the multiple choice questions on microfluidics concepts.

Table 5- Descriptive Statistics for Students' Verbal Explanations on *Microfluidics*

Group	N	Mean Gain	Std
Experimental	30	4.10	1.769
Control	30	0.63	.890

Discussion & Conclusion

Since prior work has demonstrated that even advanced engineering students still hold misconceptions about fundamental concepts in thermal sciences and other scientific subjects [1], this study was intended to test whether the schema training framework was effective in helping repair engineering students' misconceptions in diffusion, heat transfer, and microfluidics. According to the quantitative results, it seemed that the schema training approach was effective for both the diffusion and microfluidics but not for heat transfer. We suspected that there was a "pedagogic learning impediment" (10, p .165), meaning that prior education or coursework might have interfered with students' understanding of some difficult heat transfer concepts, such as energy and heat transfer. However, this is an intriguing assumption; future research will be needed to further examine the effect of the pedagogic learning impediment. It is possible that the heat transfer concept assessment questions did not adequately probe for understanding of emergence. Therefore, we could only partially answer the first research question at this point. We are revising the assessment questions for a second round of testing.

For the second research question, qualitative analysis of the students' verbal explanation of their question choices found a difference in the amount of "emergent" language used between the experimental and control groups for both diffusion and microfluidics concepts. This clearly showed that some conceptual change has taken place for the experimental group after they received their instruction on the schema training modules.

Prior work also has demonstrated that students' misconceptions are strongly held and are very difficult to repair. Thus, a one day intervention such as this study might not be expected to be successful in reshaping students' schema of some difficult concepts. According to Minstrell, the process of changing understanding of a concept from the misconception to the appropriate conception usually takes a long time. [11] A one-day intervention is usually not successful in permanently changing students' conceptions. However, our results are not without precedent. Slotta and Chi[3] also found that students' misconceptions could be repaired with ontology training. So while the results are highly unusual, we do feel they will hold up with future testing.

Additionally, this study incorporated a variety of instructional strategies and used computer technologies to help participants better conceptualize the concepts and visualize the phenomena of heat transfer, diffusion and microfludics. For example, there were computer simulations on heat transfer and diffusion with user control and manipulation at both the macro and micro levels. Furthermore, interactive exercises, such as popup reflection prompts and instant quizzes were also embedded in the training materials which were useful in helping students learn the concepts of both the processes and the subjects. [12]

This study has important implications for facilitating students' conceptual change in key engineering concepts, such as diffusion and microfluidics, which have robust misconceptions that are resistant to traditional instruction. It could lead to transformational approaches to repairing students' misconceptions by helping students acquire the appropriate mental framework or schema for difficult concepts prior to any instruction. Future studies are needed to investigate whether the participants retain accurate understanding of the concepts of diffusion and microfluidics some months later.

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Appendix A –
Sample Heat Transfer, Diffusion, and Microfluidics Concept Questions to Measure Understanding of Emergent Processes

Heat Transfer

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.

Diffusion

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?

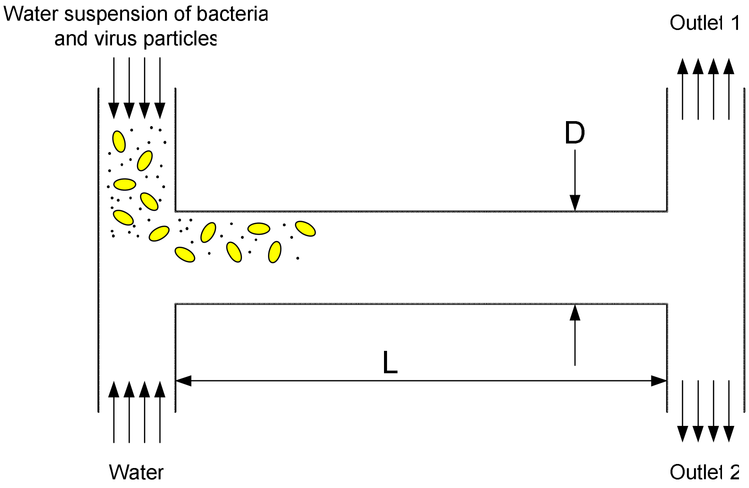
a. Random motion of sugar molecules will result in some sugar molecules moving from the balloon to the beaker; when the number of sugar molecules increases, the sweetness in the beaker will increase.
b. Collectively, the random motion of water and sugar molecules results in the proportion (concentration) 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.

Microfluidics

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}