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Using schema training to facilitate students' understanding of challenging engineering concepts in heat transfer and thermodynamics

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Abstract

Background: Chi and colleagues have argued that some of the most challenging engineering concepts exhibit properties of emergent systems. However, students often lack a mental framework, or schema, for understanding emergence. Slotta and Chi posited that helping students develop a schema for emergent systems, referred to as schema training, would increase the understanding of challenging concepts exhibiting emergent properties.

Purpose: We tested the effectiveness of schema training and explored the nature of challenging concepts from thermodynamics and heat transfer. We investigated if schema training could (a) repair misconceptions in advanced engineering students and (b) prevent them in beginning engineering students.

Method: We adapted Slotta and Chi's schema training modules and tested their impact in two studies that employed an experimental design. Items from the Thermal and Transport Concept Inventory and expert-developed multiple-choice questions were used to evaluate conceptual understanding of the participants. The language used by students in their open-ended explanations of multiple-choice questions was also coded.

Results: In both studies, students in the experimental groups showed larger gains in their understanding of some concepts—specifically in dye diffusion and microfluidics in Study One, and in the final test for thermodynamics in Study Two. But in neither study did students exhibit any gain in conceptual questions about heat transfer.

Conclusion: Our studies suggest the importance of examining the nature of the phenomena underlying the concepts being taught because the language used in instruction has implications for how students understand them. Therefore, we suggest that instructors reflect on their own understanding of the concepts.

KEYWORDS
conceptual change, heat transfer, mechanical engineering, misconceptions, schema training

1 | INTRODUCTION

Learning challenging engineering concepts is an important aspect of engineering education. However, many students develop robust misconceptions of fundamental engineering concepts that persist after instruction (Prince, Vigeant, & Nottis, 2012; Streveler, Litzinger, Miller, & Steif, 2008). Conceptual understanding of fundamental engineering concepts is critical for success in academics, and in professional engineering practices (Brown, Lutz, Perova-Mello, & Ha, 2018). Misconceptions, however, can impede engineering students' learning and contribute to lower retention in engineering programs (Yang & Miller, 2013). Too often, engineering texts present concepts as equations, making students' understanding more difficult. And students may be presented with oversimplified examples or taught in a manner that fails to uncover and correct preexisting misconceptions. Because no single strategy has yet been identified to repair all misconceptions, research that explores strategies for repairing and reducing student misconceptions is needed. Additionally, efforts to reduce the credit hours in degree programs leave less time to correct student misconceptions (Yang & Senocak, 2013). Yet, preventing misconceptions in introductory courses is crucial for students' success in upper level courses, as well as improved problem-solving, and increased retention rates in engineering programs.

This paper presents two studies that explored the use of schema training to help engineering students understand challenging engineering concepts. Study One used Chi's schema training framework (Chi, 2005; Chi, Roscoe, Slotta, Roy, & Chase, 2012; Slotta & Chi, 2006) to *repair* engineering students' misconceptions, whereas Study Two used scheme training to *prevent* their formation. The schema training framework is based on research on how learners assimilate and encode new information into an existing schema or category (National Research Council, 2000) and how they make inferences about and assign attributes to a new concept or phenomenon (Medin & Rips, 2005). However, when students learn new, challenging engineering concepts or processes, they may use an inappropriate schema and miscategorize the concept. Examples of the impact of these miscategorizations are presented later in the paper.

2 | LITERATURE REVIEW

2.1 | Misconceptions

Misconceptions are understandings that differ from accepted scientific theory (Burgoon, Heddle, & Duran, 2011). They stem from failure to fully comprehend underlying concepts (The National Academies, 1997) or are the result of the simplification or overgeneralization of complicated concepts (Chi, 2005). Misconceptions are "part of a larger knowledge system that involves many interrelated concepts" (Gomez-Zwiep, 2008, p. 437) and are "often integrated with other knowledge" that helps construct scientific understandings (p. 438). Thus, repairing and preventing misconceptions is critical. Students may develop misconceptions as they observe the world around them or from (mis)information supplied by parents, teachers, and the media (Thompson & Logue, 2006). Many factors impact a student's approach to constructing meaning that could result in misconceptions. Previous knowledge and instruction, particularly in related disciplines, play an important role (Köse, 2008). However, recognizing different kinds of misconceptions is necessary for their prevention.

Chi (2008) argued that the conventional dichotomy of right and wrong conceptions is too simple and overlooks why some incorrect knowledge is easy to correct while other misunderstandings persist. Therefore, it becomes important to closely examine how conceptual change varies. Chi characterized conceptual change as belief revision, mental model transformation, and categorical shift. Chi (2008) cautioned that these three categories are not meant to be hierarchical but rather they describe the kind of instruction needed.

When individual beliefs exhibit misconceptions, one can target and revise false beliefs with correct information (Chi, 2008). With an incorrect mental model, the organization of beliefs may be coherent but is based on flawed underlying hypotheses. Targeting individual false beliefs can lead to transforming an incorrect mental model if critical false beliefs are identified and addressed. Furthermore, "even with the best of intentions and willingness to change" (Chi, 2008, p. 72), misconceptions can still persist. In such cases, Chi suggested that a false belief and/or flawed mental model "belongs to one category and the correct conception belongs to another [conflicting] lateral or ontological category" (p. 72). This categorical conflict leads to robust misconceptions (Chi, 2008).

2.1.1 | False beliefs

Students often think of scientific topics "like heat, light, or electric current [as] an actual substance" (Reiner, Slotta, Chi, & Resnick, 2000, p. 7). For example, heat is seen as a substance that can flow from one place to another and be contained within a definite physical location. This substance-based model is frequently used to teach fundamental concepts in science and engineering and might lead to more resistant misconceptions because students "typically resist giving up their pre-instructional beliefs" (Chinn & Brewer, 1993, p. 2) in the face of new, conflicting information. Chi (2008) suggested that these substance-based models should be avoided (e.g., "shut the door, you will let the cold in") and replaced with a new "process" language.

2.1.2 | Flawed mental models

Constructivists assume new knowledge is built upon one's prior knowledge. However, this becomes problematic when the student's prior knowledge about a specific concept is incorrect, and they apply this reasoning to similar events (e.g., heat moves in the same manner as water). The constructivist approach also requires students' active involvement in potentially adapting and reorganizing their thoughts (Driver, 1989). It may be difficult for students to understand various emergent processes if they lack the emergent process schema (Chi, 2005).

2.1.3 | Category conflict and robust misconceptions

Chi (2005, 2008) labeled persistent misconceptions as "robust." Chi and other researchers suggested that at the root of these robust misconceptions is an "ontological miscategorization of a concept" (Henderson, Langbeheim, & Chi, 2017, p. 26) because students lack the existing framework to understand the complicated process. For example, conduction, convection, and radiation (the three main modes of heat transfer) processes may seem obscure to naïve students and they could confuse energy or heat with temperature.

Misconceptions are prevalent in thermal and fluid sciences and persist even among advanced engineering students (Miller, Streveler, Yang, & Santiago Román, 2011). For example, more than 50% of engineering students' responses to questions on heat transfer were in clear violation of the Second Law of Thermodynamics (Miller, Streveler, Olds, et al., 2006).

2.2 | Strategies to remedy misconceptions

To date, no single strategy has been identified to successfully repair all misconceptions. Previous studies have focused on identifying and correcting science and engineering misconceptions after they have formed (Yang & Senocak, 2013). To repair a misconception, students must acknowledge the difference between how the concept actually behaves and their expectations of what will happen and also "overcome their (perhaps even innate) predisposition to conceive" them differently (Chi, 2005, p. 161). The commonly used strategies are (a) "using conceptual conflict to confront and contradict misconceptions" and (b) using computer simulations and "inquiry-based activities (such as problem-based learning)" to promote conceptual changes (Yang & Senocak, 2013, p. 2).

2.3 | Schema training framework

A schema is a "cognitive structure that enables problem solvers to recognize problems as belonging to a particular category" (Paas, 1992, p. 429). The goal of schema training is to intentionally modify the learner's cognitive structure, highlighting the relevant and important aspect of a category. The results of using schema training to repair misconceptions in different subjects and with different ages are promising (Yang & Senocak, 2013). For example, middle and high school students performed statistically better on a posttest of diffusion concepts after receiving an intervention to help them form an "emergent process" category (Chi et al., 2012). Similarly, schema training was effective for helping middle school students solve mathematics word problems on fractions and percentages (Jitendra & Star, 2012). Schema training was also reported to assist students with future problem solving (Powell

et al., 2009). Jitendra and Star (2012) reported that schema training might be effective because it provides specific strategies for students.

2.3.1 | Sequential processes

Chi and her colleagues argued sequential and emergent processes occur within systems (Chi, 2005; Chi et al., 2012; Slotta & Chi, 2006). Sequential processes are easier for students to understand because they are visible in everyday life. For example, construction workers and construction materials are agents in a sequential process of building a sky-scraper (Miller, Streveler, & Slotta, 2006). Each worker behaves according to the task they must perform. The actions and interactions of the agents create different aspects of the process for building the skyscraper. The steel workers make the building taller, whereas the electricians install the wiring, for example. The interactions among the agents must often occur in a sequence. For example, the architect and engineers must first develop a blueprint; then other workers erect the framing and walls, and then the electricians install the wiring. Because various elements of the pattern within a sequential process are directly caused by interactions among some agents or groups (e.g., the electricians), processes like building a skyscraper are sequential. A student can *see* the process happening, and the agents within the process have distinct roles that contribute to the process.

2.3.2 | Emergent processes

By contrast, emergent processes are more complicated than sequential processes. Emergent processes are the properties of a system in which the constituent agents interact collectively and with equal status in a random and simultaneous pattern (Chi et al., 2012). Rather than a pattern being caused by the apparent "additive summing or chaining of a sequence of subevents" (Chi et al., 2012, p. 10), the pattern in emergent processes is the net effect caused by the collective summing of all the interactions. For example, a drop of dye diffusing in a cup of water is an emergent process. The molecules of dye and water (e.g., the agents) move randomly and simultaneously during the process of diffusion, behaving in a similar but independent way. The individual agents all have a similar role in creating the diffusion phe-nomenon (e.g., the pattern) of the dye mixing within the water. It is difficult to directly observe emergent processes, especially how their agents interact with each other. Thus, it can be difficult to attribute cause and effect relationships (Webb, Senocak, & Yang, 2014), and as a result, students often tend to mistake emergent processes with sequential processes. Traditionally, most emergent concepts are explained in the language of sequential processes (Miller, Streveler, Olds, et al., 2006), which may create misconceptions for students. Table 1 presents some distinctions between the two kinds of processes according to Chi's (2006) schema framework.
As it highlights, understanding the roles of the constituent agents of a system is vital to understanding the differences between emergent and sequential processes.

2.4 | The schema training method

Many of the concepts that engineering students struggle with, such as heat transfer and electricity, can be characterized as emergent processes. Emergent process 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

TABLE 1 Comparisons of sequential and emergent processes

Sequential processes	Emergent processes
Agents have individual responsibility	Agents interact collectively with equal status
Specific agents with distinguishable roles working together to create patterns	All agents interact with each other simultaneously to create patterns
Agents are restricted to other agents with which they can interact	Agents are unrestricted in their interactions
Some agents have a more important role in forming the pattern	None of the agents make a larger contribution than any other
Interactions often must occur in some sort of order and can terminate	Interactions are random and simultaneous and continue indefinitely

the scientifically normative view (Chi, 2005). Slotta and Chi (2006) developed schema training to help students distinguish between sequential and emergent processes, thus increasing their conceptual understanding of challenging concepts.

To help students learn concepts of the emergent process ontology, instruction should first identify the ontology and provide them with some of its rich examples and properties (Slotta & Chi, 2006). This approach would help students develop an appropriate ontological category that would make subsequent concepts easier to understand by helping them assimilate new information into existing schemas and infer and assign attributes based on existing knowledge.

2.5 | Conceptual change

Conceptual change occurs when students change their understanding of concepts and the frameworks surrounding those concepts (Jonassen & Easter, 2012). Gregoire's (2003) Cognitive Affective Model of Conceptual Change (CAMCC) suggests change occurs based on the individual's prior beliefs, goals, and attitudes. Change begins when learners "are presented with reform [new] messages in a particular environment" (Jonassen & Easter, 2012, p. 102). Similarly, Dole and Sinatra's (1998) Cognitive Reconstruction of Knowledge Model (CRKM) suggests the learner's characteristics and the characteristics of the message influence cognitive change. These theories point out that both the instruction and learner are important for correcting student misconceptions, and align with Chi's (2005, 2006) schema training framework.

This paper presents results from two studies that investigated the use of the schema training framework to help undergraduate engineering students understand concepts from diffusion, thermodynamics, heat transfer, and microfluidics. Study One modified and tested schema training strategies to help advanced engineering students *repair* misconceptions that had already developed about small-scale dynamic processes. Study Two tested if using emergent process language to explain challenging engineering concepts could help beginning engineering students understand these concepts and *prevent* misconceptions before students completed any coursework in thermodynamics or heat transfer.

Both studies shared similar experimental designs and data analysis. However, there were three major differences between the studies: (a) research focus (repairing vs. preventing misconceptions), (b) research design (one vs. two experimental groups: pre- and posttests vs. pre-, post-, and final tests), and (c) participant populations (advanced vs. beginning engineering students). The following presents the two studies separately in detail.

3 | STUDY ONE

3.1 | Purpose of the study

Chi posited that robust misconceptions would occur when students miscategorize emergent and sequential processes; thus, helping students understand emergent processes could improve their understanding of these misconceived concepts. We adapted Slotta and Chi's (2006) schema training modules and tested them with engineering students to see if the training modules could help repair student misconceptions in heat transfer. Previous work has shown misconceptions about heat transfer to be robust—even with advanced engineering students (Prince et al., 2012; Yang, Streveler, & Miller, 2010)—thus, presenting a ripe conceptual area for schema training interventions.

3.2 | Research question

Would instruction in schema training repair misconceptions about diffusion, heat transfer, and microfluidics with advanced engineering students?

3.3 | Method

3.3.1 | Participants

Participants were engineering undergraduates at a public university in the Midwestern U.S. with a large engineering population. Because this study hoped to repair pre-existing misconceptions, participants needed to have completed at

least one heat transfer course. To recruit students, an email invitation was sent to engineering departments whose students were likely to have completed a heat transfer course. Students were offered a monetary incentive to complete the web-based modules at a campus computer lab where a research assistant was on site to answer questions. Sixty participants were randomly assigned to evenly populated control and experimental groups. The majority of the participants were males (61.7%), but females were overrepresented compared to the total population of women in engineering at the study site. No other demographic data were collected.

3.3.2 | Modifying the schema training modules

Study One adopted an experimental research design. The study materials, including the training modules, were carefully designed to use language and content appropriate for engineering students and were evaluated by Chi and Slotta and engineering content experts (Miller et al., 2011; Yang et al., 2012).

Two sets of web-based modules (one each for the experimental and control groups) were created in a password-protected Learning Management System. Each set contained training materials and instruction about the target concepts (Table 2) and had equivalent reading levels, degree of interactivity, and number of illustrations. In the experimental group, the training modules presented sequential and emergent processes, the differences and similarities between the two, and some examples of both processes (Table 1). In the control group, the description of emergent processes in the training modules was replaced with a discussion of the nature of science.

The targeted instruction modules for experimental and control groups discussed three concepts: dye diffusion in water, heat transfer (specifically conduction and convection), and microfluidics (included as an example of far transfer of learning). Only the diffusion instruction differed between experimental and control groups where the concept of dye diffusion in water was referenced as an emergent process for the experimental group.

3.3.3 | Assessment

All participants were given pre- and posttest multi-choice questions from the Thermal and Transport Concept Inventory (TTCI), which was systematically developed (refer to Streveler et al., 2011, for details), as well as "test for understanding" multiple-choice questions about diffusion, heat transfer, and microfluidics created by content experts. To explore student reasoning about their answers, participants were asked embedded, open-ended questions to explain their choices in the multiple-choice questions. Table 2 shows the research procedures with the pre- and posttest as well as the training content for both groups.

Conceptual understanding in Study One was assessed through (a) multiple-choice questions for testing understanding of the dye diffusion in water (17 questions) and microfluidics modules (7 questions), and questions adopted from the TTCI on heat transfer modules (21 questions) (Yang et al., 2010) and (b) through students' written responses to the open-ended questions (10, 8, and 10 for dye diffusion, microfluidics, and heat transfer, respectively) to explain their multiple-choice question responses. To evaluate the open-ended responses, we used the coding scheme developed by Slotta and Chi (2006) (see the Appendix) and further elaborated upon by Yang et al. (2010) to identify and count the number of instances of emergent and sequential language contained in the responses. Two graduate students coded the data using a numerical count of verbal predicates in the responses that were attributed to sequential or emergent language. Initially the two graduate students coded the same data independently and discussed any disagreements. Then, the two coders

TABLE 2 Study one design

Procedure	Experimental group	Control group
Pretest	Dye diffusion in water; heat transfer (conduction and convection); microfluidics	
Training module	Sequential and emergent processes (see Table 1)	The nature of science; equivalent in reading level, degree of interactivity, and number of illustrations to sequential and emergent processes
Target concepts instruction and posttest	Dye diffusion in water; heat transfer (conduction and convection); microfluidics	

TABLE 3 Summary of Study One results

	Quantitative differences in multiple-choice answers	Difference in amount of emergent language used
Dye diffusion	Experimental group significantly higher	Higher emergent language in experimental group
Heat transfer	No differences	Neither group uses emergent language
Microfluidics	Experimental group significantly higher	No difference in amount of emergent language used

performed a mixture of shared and independent coding. Roughly 30% was shared coding with an inter-rater reliability of 90% (above the minimum acceptable threshold of 75%; Graham, Milanowski, & Miller, 2012).

3.4 | Results

There was a significant difference ($p = .037$) in the posttest gains (i.e., posttest means minus pretest means) between the control (M = 13.87) and experimental (M = 15.4) groups for dye diffusion concepts. There was also a significant difference ($p = .027$) in the posttest gains between the control (M = 2.77) and experimental (M = 3.60) groups for microfluidics concepts. However, there was no significant difference ($p = .823$) between the control (M = 0.97) and experimental (M = 1.10) groups for heat transfer concepts. The results suggest that the schema training approach did help the engineering students in the experimental group understand dye diffusion and microfluidics concepts. We further analyzed the written responses to the open-ended questions and found a difference between the control and experimental groups in the amount of emergent processes language used for dye diffusion. For microfluidics, however, there was no difference in the amount of emergent language used. For heat transfer, we found that neither group used emergent language. Study One's results suggest that schema training had an impact with learning dye diffusion in water and microfluidics but not with heat transfer (conduction and convection) (Table 3). Why did this happen?

Participants in Study One had completed a minimum of one heat transfer course. But students who completed more than one course actually performed more *poorly* (Yang et al., 2010). This finding aligns with research that suggests some instruction results in the formation of a learning impediment (Köse, 2008) and that it may be too late to correct their misconceptions by the time students have completed fundamental engineering courses. After completing several thermo-fluid courses, students' knowledge in the subject is firmly rooted in their mental models, making it difficult for them to think differently (Yang & Senocak, 2013). Even if students' knowledge is modified, most students regress to their previous misconceptions after a period of time (Lyddy & Hughes, 2012), making the *prevention* of misconceptions crucial. With this in mind, we wondered what effect schema training might have on students who had not yet completed any heat transfer courses, which led to Study Two.

4 | STUDY TWO

4.1 | Purpose of the study

Study Two tested a strategy to prevent misconceptions before students completed relevant coursework. In Study Two, schema training consisted of presenting learners with domain-general and domain-specific instruction based on Chi's (2005, 2006) schema training framework to help students form mental representations of scientific processes. The domain-general training utilized the same training materials (Table 2) used for the experimental group in Study One. The domain-specific training referred to the explanations of the engineering concepts in emergent processes language (Yang & Senocak, 2013). The domain-general and domain-specific strategies provided a concrete context to make learning new concepts easier for engineering students, potentially shortening the time for forming correct conceptual understandings.

4.2 | Research questions

1. Is the schema training approach effective in facilitating student conceptual understanding of challenging thermodynamics and heat transfer concepts?

2. How do the participants in the different groups (Experimental Group [EG] One and Experimental Group [EG]) Two) who receive different interventions (no schema training, domain-general, and domain-specific training) explain their understanding of some thermodynamics and heat transfer concepts?

The assumption was that using the language of emergent processes to explain challenging concepts in temperature and pressure, convection, conduction, and radiation would prevent misconceptions and provide a strong, appropriate foundation of conceptual understanding.

4.3 | Method

4.3.1 | Participants

Participants had completed pre-requisite college-level chemistry, physics, and math courses, and were enrolled in but had yet to complete any courses related to thermal and fluid sciences. The students were recruited from introductory thermodynamics and heat transfer courses at a public university in the Northwestern U. S. Participants were randomly assigned to one of three different groups: two treatment groups and one control group (Table 4). One hundred sixty-one participants completed the study, with 98 from the thermodynamics course and 63 from the heat transfer course. The majority of participants were male (86.2%), and mechanical (91.6%) and civil engineering (5.4%) majors in their junior (67.9%) year of college. Participants were recruited within the first 3 weeks of the semester. They were offered extra credit from their instructors in addition to a small monetary incentive for their participation. Data were collected over two semesters with different participants.

4.3.2 | Training materials and research procedure

Study Two used an experimental design and collected both qualitative and quantitative data. Participants were randomly assigned to one of three computer-based modules in Moodle, an online course management system (Table 4). The modules included (a) the control group module with concepts instruction adopted from engineering textbooks; (b) the EG One module with schema training (the same used for the experimental group in Study One) and the same concepts instruction for the control group; and (c) the EG. Two module with schema training and the concepts described in the language of emergent processes. The concepts instruction included heat transfer (conduction, convection, and radiation) and thermodynamics (temperature and pressure). Participants' learning gains of the heat transfer and thermodynamics concepts were evaluated through pre-, post-, and final tests.

Participants completed a pretest at the beginning of the study to determine relevant prior knowledge. After completion of the pretest, the three groups received instruction on fundamental concepts in thermodynamics or heat transfer via a learning module that took approximately 45 to 60 min to complete. The experimental groups also received instruction differentiating emergent processes from sequential ones (schema training) and included examples of the different types of processes. The control group received a lesson that took the same amount of time as the schema training module. At the end of the training, participants took a posttest. During the last 3 weeks of the same semester

TABLE 4 Study two design

Control group	EG One	EG Two
Pretest—beginning of the semester		
The nature of science (equivalent to schema training module)	Schema training module (domain-general, see Table 1)	Schema training module (domain-specific; see concepts instruction below)
Heat transfer ($n = 18$); thermodynamics ($n = 32$) module (adopted from textbook)	Heat transfer ($n = 21$); thermodynamics ($n = 37$) modules—same as control	Heat transfer ($n = 24$); thermodynamics ($n = 29$) modules—explained the concepts in emergent processes language
Posttest—after computer-based training		
Final test (same as the pre- and posttest)—end of the semester		

Note: n stands for number of participants in each group from each course who completed all three tests (pre-, post-, and final).

while the participants were finishing their first thermodynamics or heat transfer class, they were asked to complete the final test to determine if the training had any impact on learning throughout the semester.

Conceptual understanding was similarly assessed as in Study One. Questions regarding thermodynamics concepts were adapted from the TTCI (Miller et al., 2011) and were modified by two engineering faculty who taught undergraduate thermodynamics courses. There were 11 thermodynamics concepts questions, including 9 multiple-choice questions and 2 written-response questions that asked the participants to explain their multiple-choice responses. Heat transfer questions included 11 multiple-choice questions based on the TTCI and 4 written-response questions created by two engineering faculty. Both sets of questions were reviewed by two engineering education researchers and modified accordingly in hopes of both capturing the use of emergent language in students' open-ended explanations and providing cues for participants to explain their responses in emergent language.

4.3.3 | Concepts explained as emergent processes in Study Two

Two engineering faculty members who taught thermodynamics and heat transfer worked closely with one education researcher to select the concepts and explain them in emergent processes language. Temperature and pressure were chosen from the thermodynamics course, and conduction, convection, and radiation were from the heat transfer course. *Temperature* was explained as a macroscopic property that emerges from the random motion of molecules with a distribution of kinetic energies. *Pressure* was explained as a microscopic manifestation of individual molecular collisions and as a macroscopic property that emerges from the random motion of individual molecules colliding with a solid surface. *Heat transfer* (conduction, convection, and radiation) was explained as an emergent process too. For example, conduction in liquids and gases was presented as random molecular collisions, while conduction in solids was presented as movement of free electrons, which is essentially the same mechanism for electric current flow in solids. Free convection is an emergent process as well because the convective flow can be presented as fluid motion resulting from its density differences due to temperature gradients. Thermal equilibrium is another emergent phenomenon that students often see as "direct and causal" because energy transfer via molecular motion seems to stop when equilibrium is reached. In fact, the motion continues, but no net energy transfer occurs.

4.4 | Results

4.4.1 | Quantitative results for thermodynamics concepts

A one-way between-group repeated measure of analysis of variance with the pretest as a covariance (ANCOVA) was conducted to examine the impact of the training on participants' knowledge of thermodynamics as measured by the questionnaire for the posttest. The use of ANCOVA took the participants' pretest into consideration as a covariance. There was no significant difference between the three groups of participants on the posttest of thermodynamics ($F(2, 94) = 0.181$, $p = .835$). Similarly, an ANCOVA was conducted to examine the impact of the training on participants' knowledge of thermodynamics as measured by the questionnaire for the final test. After adjusting for pretest scores, there was a significant difference among the three groups on participants' performance ($F(2, 94) = 3.445$, $p = .036$) for the final test.

Furthermore, post hoc comparisons showed that the EG One's mean ($M = 5.994$, $SD = 0.248$) was significantly higher ($p = .039$) than that of the control group's mean ($M = 5.067$, $SD = 0.268$). Although the EG Two ($M = 5.796$, $SD = 0.281$) had a larger overall mean than that of the control group, it was not significantly different ($p = .192$) from either the control group or EG One.

However, there was no significant difference among the three groups of participants' posttest scores for thermodynamics or heat transfer. There was also no significant difference among the three groups of participants' post- or final test scores for heat transfer.

4.4.2 | Quantitative results for heat transfer concepts

An ANCOVA was conducted to examine the impact of the training on participants' knowledge of heat transfer as measured by the posttest. There was no significant difference among the three groups in the posttest ($F(2, 59) = 1.223$, $p = .302$). Similarly, an ANCOVA was conducted to examine the impact of the training on participants' understanding

as measured by the final test. After adjusting for pretest scores, there was no significant difference among the three groups on participants' knowledge of heat transfer in the final test ($F(2, 59) = 0.027$, $p = .974$).

4.4.3 | Qualitative data analysis

Because there was no significant difference among the three groups of participants for the heat transfer concepts, the participants' written responses to multiple-choice questions were further examined. The written responses for one question (described below) that best solicited the emergent process language were chosen for analysis because the researchers experienced challenges in explaining heat transfer concepts in the language of emergent processes and anticipated the same challenges from the participants.

When trying to explain heat transfer concepts, some phenomena did not fall neatly into either the sequential or emergent processes categories. For example, neither convection nor radiation could be adequately explained in emergent process language alone. Radiation does not involve random molecular movement, while convection does involve molecular collisions near the fluid–solid interface (the boundary layer). Because of the complexities of these phenomena, they are not completely described as either emergent or sequential processes and, therefore, might not be good candidates for repair through schema training.

The following question regarding the mixing of hot and cold water was chosen for analysis because it specifically solicited emergent themes and depicted a more straightforward emergent process.

Hot and cold water mixing: Two beakers connected by a short tube with a valve as depicted in Figure 1. Beaker #1 contains hot water and Beaker #2 contains cold water, creating a temperature difference between the two. Each beaker contains the same amount of water. Density changes due to temperature are negligible.

At first, the valve on the tube is closed, so nothing happens in the two beakers. When the valve is opened, a thermometer in each beaker shows that Beaker #1's temperature decreases and Beaker #2's temperature increases. Which of the following statements best describes the underlying physics of the cold beaker temperature increasing and the hot beaker temperature decreasing?

a. It is caused by the exchange of energy between water molecules.
b. It is caused by the movement of cold water molecules from the cold beaker to the hot beaker.
c. It is caused by the movement of hot water molecules from the hot beaker to the cold beaker.
d. The combined effects of the exchange of energy and exchange of molecules between the two beakers.

The written response prompt asked the students to refer to the temperature change between the two connected beakers and then answer two questions: How do the hot water molecules spread from the hot beaker? How would molecules spread once thermal equilibrium is reached between the two beakers?

A written response based on the emergent process language could be: The water molecules spread randomly due to the random interactions and movements of the molecules. There is also energy exchange because of molecular collisions between hot and cold molecules. Because the average kinetic energy of the molecules in the hot beaker is higher, the net movement of molecules will be from the hot to the cold beaker. In this case, the agents have equal roles—both hot and cold molecules diffuse, and the water molecules are still moving randomly after equilibrium is reached. However, some students held the misconception that only hot water molecules move, and some students held the misconception that the molecules stopped any motion once the equilibrium was reached. This question about hot and cold water mixing anticipated that molecular motion is a constant and random process for both agents (i.e., cold and hot molecules), not just for the hot water molecules. Students who had received the training in the sequential and emergent processes were expected to use language that revealed the random and constant motion of both agents (hot and cold water molecules).
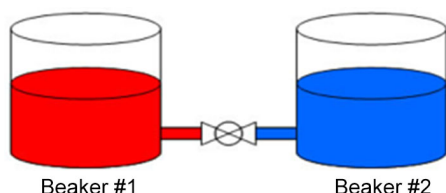
FIGURE 1 Two connected beakers [Color figure can be viewed at wileyonlinelibrary.com]

The participants' responses to this question were analyzed from pre-, post-, and final tests for the control and the two experimental groups. Responses were coded to determine if different explanations or emergent language was expressed. The coding scheme (Table 5) was adapted from the one used in Study One (see the Appendix) based on the researchers' experience in trying to explain both thermodynamics and heat transfer concepts in emergent processes language. Specifically, the researchers looked for the emergent themes in the participants' responses seen in Table 5.

4.4.4 | Qualitative analysis results

Some participants did not refer to the motion of molecules but instead focused on heat and energy transfer, which was coded as no verbal indicator. Net heat and energy transfer can stop, but the molecules still have motion even if equilibrium is reached. For example, one participant wrote, "The molecules would cease to exchange energy with each other once thermal equilibrium was reached." This response is a partially correct answer from a molecular point of view. The net exchange of energy would be zero. However, this response did not address the motion of the molecules, so it was coded as "no verbal indicator." Written responses from 15 participants in the control group, 15 participants in the EG One, and 19 participants in the EG Two were coded. Table 6 presents the coding results.

The coded themes of sequential and emergent language were further displayed as percentages in Figure 2. It shows that the EG One and EG Two groups included more emergent themes in their written responses, while the control group had fewer emergent themes but more sequential language after the training period.

For the first research question regarding the effectiveness of the schema training, the experimental group that received the schema training performed statistically better than the control group of participants on the thermodynamics final test (Table 7). For the second research question regarding the use of emergent language, the participants in the experimental groups used more emergent language to explain their understanding of challenging thermodynamics and heat transfer concepts. For example, a participant in the EG Two group explained in the final test, "The molecules don't move from one side to the other, they exchange energy and spread the energy evenly to both beakers once steady state is reached," indicating their understanding of continuous and random motion (coded as EP2). Other participants were able to identify the random motion of molecules (e.g., "Once equilibrium is reached the molecules will continue to bounce around between the two beakers at a random rate"). By including the qualitative results for participants' use of emergent processes language on the heat transfer concept, we were able to show that there was a difference between the groups' use of processes language (Figure 2). Thus, our alternative hypothesis was partially

TABLE 5 The schema training coding scheme

Emergent themes	Sequential themes
Moves randomly	Restricted/not randomly
Acts simultaneously	Not acting simultaneously
Is continuous	Terminated

TABLE 6 Frequency of coding results

Code	Control (*n* = 15)			EG One (*n* = 15)			EG Two (*n* = 19)		
	Pretest	Post	Final	Pretest	Post	Final	Pretest	Post	Final
No verbal predicate	6	2	3	3	6	3	6	5	3
EP	8	7	6	8	11	12	7	12	15
SP	5	10	10	8	4	7	9	4	8
EP+SP	0	0	3	2	0	0	2	0	1
EP3	0	0	0	0	1	1	0	0	0
EP2	2	2	0	0	0	0	2	2	7
SP2	1	2	0	1	0	0	2	0	0

Abbreviations: EP, emergent process; EP2, two incidences of EP; EP3, three incidences of EP; SP, sequential process; SP, two incidences of SP.
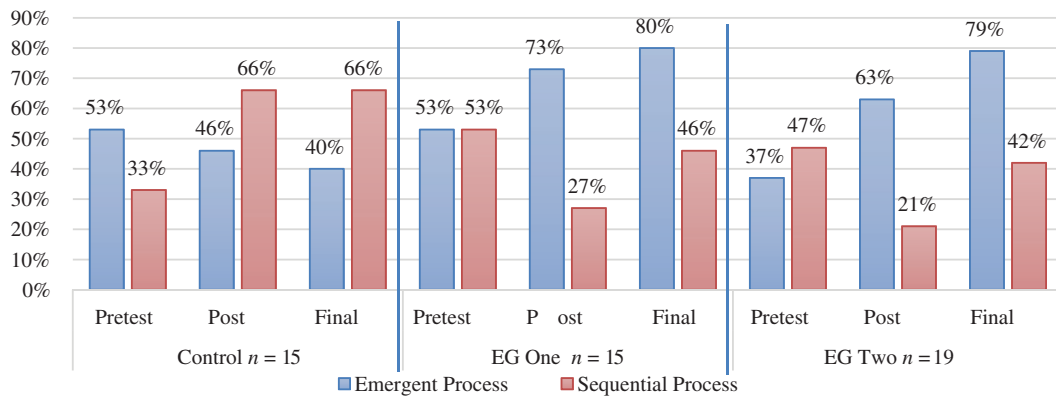
FIGURE 2 Sequential and emergent themes for all participants in three tests. The Y-axis stands for the percentage (frequency divided by participant number in each group) of the sequential or emergent language found [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 7 Summary of Study Two results

	Quantitative differences in multiple-choice questions	Emergent processes language used in written responses
Thermodynamics	EG One had a significantly higher mean in the final test	N/A
Heat transfer	No differences	Higher percentages of emergent processes language in EG One and EG Two; lower percentage of emergent and higher percentage of sequential process language in control group

supported. The results for Study Two demonstrate that participants in the experimental groups who received instruction differentiating emergent processes from sequential ones were able to develop greater understanding of emergent processes. The schema framework seemed to have helped students understand some invisible processes at the molecular level.

5 | DISCUSSION

Studies One and Two confirmed the challenges in repairing robust student misconceptions. Reducing students' misconceptions could decrease frustration and promote greater academic performance. In turn, this could help increase the number of students pursuing degrees and careers in engineering.

Underlying the studies reported here was the intriguing idea proposed by Chi and colleagues (Chi, 2005, 2008; Slotta & Chi, 2006) that helping students understand the conceptual category of emergent processes could also help them better understand challenging engineering concepts. Testing this idea within the engineering domain, our studies have implications for engineering instruction and for strengthening the credibility of Chi's theory. Our results are promising, if not definitive. In both studies, engineering students who completed online schema training modules were generally more successful in answering some domain-specific conceptual questions than those who completed a similar web-based module without schema training instruction. And in both studies, there were differences in the amount of emergent language that was spontaneously used by students to explain their answers in writing. In Study Two, which included a semester-end final test as well as a posttest at the end of the training module, the use of emergent language persisted.

What is perhaps most intriguing and perplexing is why the schema training was successful with some topics but unsuccessful with others. In Study One, the experimental group had a significantly higher gain score in the dye diffusion and microfluidics sections than for heat transfer. In Study Two, there was also no significant gain in heat transfer scores but there was some gain in the final test for thermodynamics. Perhaps something about the heat transfer concepts makes them less appropriate to be described with emergent processes language. This suggests that it is vital to closely examine the nature of the concepts being learned.

6 | CONCLUSION

It occurs to us that the equations and models used to understand heat transfer problems (and many engineering problems in general) may reinforce thinking about these phenomena as sequential rather than emergent processes. Some sequential explanations of phenomenon are still used even though they are not strictly accurate (e.g., describing laminar flow as parallel layers of fluid sliding over each other like a deck of playing cards) and may unintentionally strengthen misconceptions. Furthermore, students are not always clear that boundary conditions are imposed upon a system (such as in heat transfer) and that these conditions are not a characteristic of the system itself, or that process end points and terminal activities are not necessarily the same despite occurring simultaneously (e.g., equilibrium states). Moreover, some concepts (e.g., heat transfer in hot and cold water mixing, and radiation) may have some but not all characteristics of an emergent or sequential category, implying that a category in between emergent and sequential may exist, which could explain why schema training works in certain instances (dye diffusion and microfluidics) but not in others (heat transfer).

Another exciting potential explanation for our results is found in our examination of the role of agents in a system. As illustrated in Table 1, an important distinction between emergent and sequential processes is that in an emergent phenomenon all agents have the same role and make the same contribution to the system. But our findings suggest that perhaps some phenomena in heat transfer (specifically convection and radiation) do not meet these criteria. Convection involves conductive heat transfer at the solid–liquid interface, but action of the agents will not be apparent to undergraduate engineering students, while radiation does not involve molecular agents at all. Evidence for this speculation lies both in experts' difficulty in creating descriptions for these phenomena using emergent processes language and in participants' responses to the open-ended questions about the hot and cold water molecules mixing in the heat transfer problem. Participants were able to provide a scientifically correct explanation of the phenomenon that used sequential rather than emergent language. Thus, instead of a dichotomous distinction of "sequential" and "emergent" processes, some phenomena may have some properties of both. This might seem like an esoteric distinction, but if learning about emergent properties is useful for some phenomena but not for others, then it is important to have a deep understanding of the phenomena so that appropriate instruction can be used.

6.1 | Limitations

There are several limitations to the study. First, learning is an extremely complex process, influenced by a myriad of factors. To make the study manageable, we focused on a small set of concepts. Additionally, the sample size in Study Two for the heat transfer instruction was relatively small (Table 4). Replications with additional concepts and a larger sample size are recommended. Furthermore, the demographics of the participants in the studies were predominantly male, and repeating this study with a more diverse population would help identify differences for traditionally underrepresented or marginalized students in learning challenging concepts.

Second, some participants focused only on the phenomenon (the energy transfer) instead of the underlying mechanism (the motion of the molecules), failing to grasp that the goal of schema training was to promote their understanding of the underlying mechanism of the phenomenon. For example, one participant wrote, "The molecules from the hot beaker have higher energy and therefore move faster than [those of] the cold beaker. Once the beakers reach an equilibrium the exchange of energy would stop." This response did not mention the interaction and exchange between the hot and cold water molecules or that the molecules are still in motion although the net exchange of energy would stop. Therefore, future studies could focus on helping participants think about a phenomenon at the molecular level (Webb et al., 2014).

Another potential limitation may lie in the all-or-nothing assumption upon which schema training is based. Chi represents the switch from a sequential to emergent way of thinking about processes as happening completely or not at all. But others have proposed a transitional or liminal space between students' old and new ways of thinking (Meyer & Land, 2005), or that fragmented, "synthetic" frameworks are created when students incorporate scientifically correct information into their prior naïve frameworks (Vosniadou, 2013). Clearly, examination of transitional stages of understanding is needed.

Finally, the results cannot be generalized to all engineering students given the participants were primarily male students. Similarly, these results may not be generalizable across other demographic indicators including race and ethnicity.

6.2 | Future research

The schema training framework could be refined and improved. For example, two of the characteristics listed in the current framework, "Agents have individual responsibility" and "Agents interact collectively with equal status in a similar way," seem to apply only to certain invisible, emergent processes. These traits apply when explaining the process of dye diffusion in water because there is no distinguishable difference in motion or roles between the water and dye molecules. However, it is uncertain whether they apply to the explanation of energy transfer when hot and cold water are mixing. The hot water molecules are moving faster than the cold water molecules although both hot and cold water molecules still have random motion and collisions with other hot and cold molecules.

Also note that a collection of molecules at the same temperature do not all have exactly the same velocity—there is a distribution, which on average results in the measured temperature. While it is scientifically accurate to say that the agents (hot and cold water molecules) play slightly different roles during the process of mixing, the current schema framework wording may be based on the diffusion of dye into water, where the molecules of water and dye behave the same in the process of diffusion before the state of equilibrium. Future research could fine-tune the schema training framework and develop emergent language explanations of challenging concepts. Finally, investigating emergent language in students' verbal explanations warrants additional study, and using writing to help promote the conceptional understanding of engineering concepts (Rouse & Rouse, 2019) should be explored.

These studies provide a cognitive level description of teaching and learning of some concepts within engineering education. Specifically, Study Two illustrates how to describe energy and heat transfer with cold and hot water molecules in emergent language (i.e., using the emergent themes identified). Research supports the power of generic language used during childhood to shape children's concepts (Cimpian & Markman, 2009) as misconceptions may develop due to the differences between scientific and daily language (Brown & Ryoo, 2008). The use of emergent processes language in this study can further develop theoretical accounts of why some engineering and science concepts are particularly challenging to learn and teach. This study suggests that utilizing emergent processes language might mediate and even prevent misconceptions and, thus, improve engineering education.

Finally, the schema training approach originated in science education, which is typically concerned with conceptual accuracy in learning. In engineering, learning is outcomes-orientated and pragmatic. Thus, in engineering education, it is acceptable to use approximations and assumptions to simplify concepts. Since the science education and engineering education communities may have different motivations, different approaches may be needed to promote conceptual change. Thus, further investigation of the schema training approach with different science and engineering concepts is needed.

6.3 | Instructional implications

Our studies suggest the importance of thinking about the nature of the phenomena underlying the concepts being taught and learned, because the language used in instruction has implications for how students understand concepts. Therefore, we suggest that instructors reflect on their own understanding of the concepts they teach. Are the concepts we teach produced by sequential or emergent processes? And thus is the instructional language we use appropriate? In some cases, the emergent nature of a phenomenon can be obscured by an instructional overlay of sequential language. For example, we speculate that sequential thinking might be "baked in" to undergraduate instruction about heat transfer, making it difficult for students to switch to an emergent way of thinking about heat transfer in advanced courses. Although explaining concepts using emergent language can be challenging, we feel it is worth the effort to prevent misconceptions that can hamper future learning.

More importantly, instructors need to be aware that some concepts are not readily explained in either sequential or emergent processes language. When teaching challenging concepts, we recommend instructors focus on promoting students' understanding of the underlying mechanism of the concepts at the molecular level. Computer technologies, such as simulations allowing students to manipulate challenging concepts, can greatly facilitate student learning.

data analysis, or shaped our understanding of the schema training framework, especially the emergent processes. We thank Michelene Chi for allowing us to adapt the Schema Training materials.

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APPENDIX

Coding rubric for an emergent process

Code "0" – If subject does not respond, or provides an inaccurate or irrelevant response (No verbal predicates used).

Code "1" – If the subject refers to emergent themes such as "indirect," "continuous," "independent," "simultaneous," "equilibrium," or "balanced ratio of molecules" in a manner that is more suggestive of emergent processes than sequential ones (1 to 3 verbal predicates used).

Code "2" – If the subject names emergent themes such as "indirect," "continuous," "independent," "simultaneous," "equilibrium," or "balanced ration of molecules" when they are in *direct reference* to an emergent process (4 to 7 verbal predicates used).

Code "3" – If the subject names emergent themes such as "indirect," "continuous," "independent," "simultaneous," "equilibrium," or "balanced ration of molecules" when providing a clear and complete description of an emergent process (all 8 verbal predicates used).

Coding rubric for a sequential process

Code "0" – If subject does not respond, or provides an inaccurate or irrelevant response.

Code "1" – If subject refers to sequential themes such as "direct," "distinguishable," "restricted," "sequenced," "dependent," or "end/terminate" in a manner that is more suggestive of sequential processes than emergent ones.

Code "2" – If subject refers to sequential themes such as "direct," "distinguishable," "restricted," "sequenced," "dependent," or end/terminate when they are in direct reference to a sequential process.

Code "3" – If subject refers to sequential themes such as "direct," "distinguishable," "restricted," "sequenced," "dependent," or "end/terminate" when providing a clear and complete description of a sequential process.

The use of the following expressions can be used as evidence of a deep understanding of an emergent process such as dye diffusion in water.

Verbal predicates code

contributes Equally (CE) (hot and cold water molecules don't have the same roles)
moves Randomly (MR)
is Unintentional (U)
is Indirect (I)
has Equal Roles (ER) (hot and cold water molecules don't have the same roles)
acts Simultaneously (AS)
is Continuous (C)
is Independent (II)