AUGMENTING THE CLASSICAL CHANGE MODEL TO PROMOTE CONCEPTUAL LEARNING IN CORE ENGINEERING COURSES

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INTRODUCTION

The importance of conceptual learning and the limitations of traditional instruction for promoting that learning have been well documented in engineering education.[1–6] Fortunately, a number of instructional strategies have been developed that more effectively elicit conceptual change. Studies in science and engineering consistently show, for example, that active learning and inductive teaching methods are more effective than traditional lecturing for helping students to master important concepts.[7–11]

While there are numerous specific instructional practices that have been adopted to foster conceptual understanding, the specific approaches can be grouped into a small number of general categories. Limon[12] suggests that effective conceptual change strategies fall into three categories: (1) "the induction of cognitive conflict through anomalous data"; (2) "the use of analogies to guide students' change"; and (3) "co-operative and shared learning to promote collective discussion of ideas." Scott et al.[13] divide effective reform strategies into those that seek to elicit cognitive conflict to create "teachable moments" and those that seek to build on and extend existing ideas, often using metaphor or analogy. While there are other ways to categorize conceptual change strategies,[14, 15] clearly the distinction between strategies utilizing conflict and those that do not is one of the key distinctions found in the conceptual change literature.

Cognitive conflict is the core element of the "classical approach" for promoting conceptual change.[15] This classical model shaped much of the conceptual change research in the latter half of the 20th century, especially in the sciences.

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As Vosniadou points out, however, at some point almost all of the tenets of the classical approach came under attack. Consequently, engineering instructors and engineering educational researchers might draw the impression that cognitive conflict has been discredited as an effective change strategy. In this article, we present a broad literature review and two case studies that explore how the classical approach can be adapted to address the concerns noted in the literature. We also explore, utilizing case studies drawn from our own research in engineering education, the conditions under which cognitive conflict can be integrated into an effective strategy for promoting conceptual learning.

BACKGROUND

Introduction and support for cognitive conflict

The classical approach for promoting conceptual change starts by trying to bring about cognitive conflict through some means. The approach is driven from a recognition that simply providing students with correct explanations is generally ineffective for promoting conceptual understanding and that some additional motivation is required to get students to engage in the emotionally and intellectually taxing process of conceptual change. Instructional techniques that employ cognitive conflict draw on Piaget's concepts of assimilation and accommodation.[16] When faced with new information, Piaget postulated that the learner can either assimilate it (i.e., integrate it into their existing mental models) or change their mental model to accommodate information that conflicts with their current understanding. Posner and his colleagues[17] adopted this framework and identified four necessary conditions for change, the first of which is that there must be dissatisfaction with the existing conceptions. Cognitive conflict provides the basis for the "dissatisfaction" that is a precondition for change in Posner's model. Related terms are also used to describe this state. Piaget[18] referred to this dissatisfaction as "disequilibrium", while Festinger[19] used the term "cognitive dissonance." Lee and Byun[20] suggested that while these terms are not identical, they have frequently been used interchangeably in much of the conceptual change literature. They define cognitive conflict as "a perceptual state of the discrepancy between one's mental model and the external information recognized (internal-external conflict), or between different mental models of one's cognitive structure (internal conflict)." The common idea in each framework is that inconsistency or conflict causes psychological discomfort, which individuals naturally want to reduce.

Guzetti et al.[21] note a number of instructional practices designed to produce cognitive conflict. For example, Socratic teaching uses counterexamples to force students to face contradictions in their reasoning. Similarly, the use of refutational texts[22] confronts students with ideas different from their personally held beliefs. One of the most common means employed to produce cognitive conflict in engineering and the sciences is to present students with anomalous data.[20, 23, 24] As Chinn and Brewer note, [23] anomalous data can be presented to students in different ways, including laboratory experiences, classroom demonstrations, computer simulations or group discussions. Presenting anomalous data in these ways forms the foundation of many conceptual change strategies found in the literature.

Strategies designed to promote cognitive conflict have been shown to be effective for promoting conceptual change. Guzetti et al.[21] conducted a meta-analysis of instructional interventions in both reading and science education. They conclude that:

> Based on the accumulated statistical evidence from two disciplines, we have found that instructional interventions designed to offend the intuitive conception were effective in promoting conceptual change. The format of the strategy (e.g., refutational text, bridging analogies, augmented activation activities) seems irrelevant, provided the nature of the strategy includes cognitive conflict.

Chan et al.[25] found that situations that produced higher levels of conflict led to higher learning in their study. In a separate review of cognitive conflict as an instructional strategy, Limon[12] notes several studies that similarly show positive results.[26–38] Duit et al.[39] note that cognitive conflict is also an integral component of effective approaches such as the learning cycle[40, 41] and "constructivist teaching sequences".[13, 42]

Limitations of Cognitive Conflict as a Change Strategy and Implications for Instructors

While it has been widely adopted, the classical model for promoting conceptual change faces significant criticism. Limon's review of cognitive conflict[12] notes several studies where the approach fails to produce conceptual change.[21, 26, 30, 43–46] Their overall assessment of cognitive conflict as a change strategy is quite critical:

> Despite the positive effects we have reported, perhaps the most outstanding result of the studies using the cognitive conflict strategy is the lack of efficacy for students to achieve a strong restructuring and, consequently, a deep understanding of the new information. Sometimes, partial changes are achieved, but in some cases they disappear in a short period of time after the instructional intervention.

Other studies have also found that cognitive conflict often fails to promote conceptual change.[20, 23, 25, 47-50] Limon's review of cognitive conflict[12] suggested that cognitive conflict often promoted weak results, either achieving only partial restructuring of students' understanding and/or being limited in duration. Understanding when and why cognitive conflict fails to promote durable conceptual change is obviously of practical concern to instructors hoping to utilize this approach. In this paper, we will examine the effectiveness of cognitive conflict as a strategy to promote conceptual change in engineering education, with a particular focus on seeking to understand the conditions that increase the success of this instructional method in practice. We do this by first presenting two case studies that use cognitive conflict in chemical engineering. We examine the effectiveness of cognitive conflict strategies in each study and attempt to put these in context by looking at the broader literature on conceptual change strategies. Finally, we will draw conclusions about how the literature and the case studies together point towards effective implementation of cognitive conflict as an instructional strategy.

RESULTS: CASE STUDIES IN ENGINEERING

Below are two specific case studies drawn from the authors' teaching and research.[1, 47] Each case study has several features in common. First, cognitive conflict is the core component of the intervention being examined. In each case, a situation is presented in which students' misconceptions tend to lead them to mis-predict the outcome, leading to cognitive conflict. Second, the studies focus on conceptual learning as an outcome, rather than factual knowledge, problem solving, attitudes or other instructional objectives. Third, each study assesses conceptual change using a validated concept inventory in a pre-post study designed to provide explicit measures of conceptual change via the intervention employed.

Case Study 1: Cognitive Conflict to Repair Misconceptions in Heat Transfer

At the start of heat transfer courses, students typically scored less than 50% on a concept inventory targeting the ideas in Table 1.[48] In order to assess change in conceptual understanding, students took the Heat and Energy Concept Inventory (HECI) at both the start and end of the semester. Over the course of the semester, students engaged in eight inquiry-based learning activities (IBLAs) as illustrated in Figure 1. These activities asked students to predict in writing what they believed would happen in a given situation, then do an experiment (or simulation) for that same situation and, finally, write a technical reflection on what actually happened. The final scores on the concept inventory were both significantly greater than the start of the semester (46.5% to 66.1%) and significantly higher than equivalent courses offered without IBLAs (change from 49.2% to 54.4%).[48]

TABLE 1

Targeted Conceptual Areas and Common Student Misconceptions[1, 2, 48, 49] for cases 1[1, 2] and 2[47]

Concept Area	Targeted Student Misconception
1. Rate vs. Amount	Students commonly believe that factors which increase the rate of heat transfer always increase the amount of heat transferred as well. These misconceptions carry over to related fields such as mass transfer.
2. Temperature vs. Perception of Hot and Cold	Students commonly believe that temperature is a measure of how hot or cold things feel. Many students do not understand that other factors, such as the rate of heat transfer, frequently affect how hot or cold something feels.
3. Temperature vs. Energy	Students commonly believe that temperature is a direct measure of the energy in an object, so something at a higher temperature always has more energy.
4. Radiation	Students are commonly confused about the effect of surface properties such as color on the rate of radiative heat transfer, for example believing that black surfaces hold on to energy and therefore emit radiation more slowly than white surfaces.

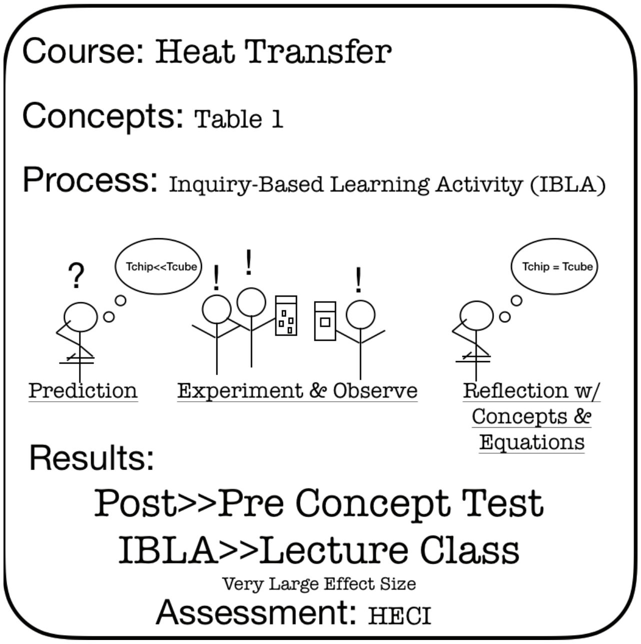

Figure 1. *Summary of Case 1, use of IBLAs based on the work of;[50, 51] assessment by Heat and Energy Concept Inventory (HECI).[1]*

Case Study 2: Cognitive Conflict as Thought Experiment and Compared to Analogy

This case also focuses on a heat transfer course in which students took the HECI both at the start and end of the semester and focused on concept areas 1 and 3 from Table 1. Students were asked to make a prediction, and then one of two interventions occurred. As shown in Figure 2, students were either asked to work with a group to design an experiment to test their prediction and subsequently shown the results of such an experiment (thought experiment) or students were presented with a more accessible analogy for the phenomenon

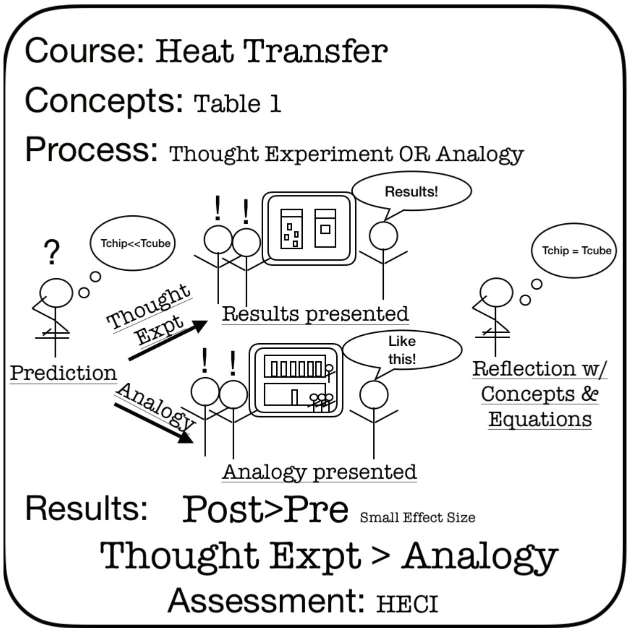

Figure 2. *Summary of Case 2, analogy based on design of,[52] thought experiment, prediction and reflection questions the same as Case 1. Assessment by HECI.[1]*

(analogy). For students using thought experiments, scores improved from 42.5% to 50% (Table 1, concept 1) and 45.3% to 66.7% (Table 1, concept 3), while students using analogy improved from 46.3% to 47.5% (Table 1, concept 1),[47] all of which were significant improvements relative to start-of-semester scores.

DISCUSSION

While these results provide significant support for the classical change model, they also support some of the criticisms of this approach. Cognitive conflict as employed in these case studies did not completely restructure student's conceptual understanding (in no case do 100% of students change to conceptually correct answers), even in the short term, nor did all of the initially measured learning gains endure over an extended period of time. A subsequent study by Prince et al [2] specifically examined these and related concerns. The authors examined how the effectiveness of the intervention varied by concept area, concept difficulty, and degree of transfer required between the activity and the assessment question. They also examined both initial and long-term impact of the activity on students' conceptual understanding to determine the degree to which students retained what they apparently learned through the activity. Several factors seemed to affect both the immediate and long-term impact of the inquiry-based activity on student learning. The results show generally high levels of retention of learning (78% retention of immediate learning gain) from the time of the intervention to the end of the semester.[2] However, both the short-term improvements in students' conceptual understanding and retention of what students apparently learned from the activity varied by concept area, difficulty and level of transfer required. This is consistent with some of the literature cited previously[14, 53] who note that different types of misconceptions should respond differently to certain types of instruction. Further analyzing the degree and durability of restructuring of student understanding, Prince et al.[2] showed that when learning failed to "stick," students disproportionately reverted to their initial misconceptions. This demonstrates that students' initial preconceptions often retain some hold on students' thinking, even after the conflict-based intervention. While it wasn't the dominant pattern, this trend did demonstrate that the intervention sometimes led to partial rather than complete restructuring of students' conceptual understanding. Overall, students experiencing and reflecting upon cognitive conflict through IBLAs scored significantly higher on post-course concept inventories than did students in courses without IBLAs.[48]

It is useful to revisit why the classical approach can fail and to examine how to get the most from this instructional strategy in practice. In what follows, we examine the limitations of the classical change strategy and possible ways to address those limitations.

One of the reasons cognitive conflict strategies fail is that students presented with anomalous information can respond in many possible ways. Piaget[18] categorized possible responses to anomalous data as either unadapted, where individuals don't realize a conflict exists, or adapted where students recognize the conflict and respond by either ignoring the data, only partially modifying one's theories in response to the data, or making changes in one's core understanding. Posner[17] similarly noted that responses to anomalous data could include rejection of the data, lack of concern, or compartmentalization of knowledge.

One of the strategies employed in the presented case studies was to have students explicitly record their initial prediction, then record their observations and then explicitly identify any differences. These or similar structures can be built into the educational materials to minimize the chances that students will fail to observe a conflict where it exists. However, these structures can still fail to modify their conceptual structures. For example, these structures may not produce learning when students' prior knowledge is so minimal they are unable to recognize a conflict.[23, 30] Students' strongly held preconceptions can also lead them to discount new information.[23] Finally, students' attitudes influence how they respond. For example, students in one study[54] did not change their views in response to conflicting information in part because they did not expect their understanding of course concepts to be coherent.

Several authors have noted conditions that helped or hindered learning when students are confronted with anomalous data.[12, 20, 23–25, 37, 55–57] Chan et al.'s analysis,[25] for example, showed that conflict enhanced learning, but only when students engaged in "knowledge-building activities". These included recognizing and attempting to reconcile inconsistencies, taking conflicting viewpoints into account, and waiting before drawing conclusions. Potvin et al note that conflict is useful as part of a teaching sequence, but not necessarily at the very beginning.[58] In the previous case studies, some of the structures employed were designed to enhance students' recognition of inconsistencies. The final step in each case, having students reflect on discrepancies and to attempt to model the observed phenomena, are examples of "knowledge building activities."

Constructivist frameworks underscore that learning builds from students' prior knowledge and that students' naïve conceptions are not simply replaced with expert reasoning as a result of being confronted with contrary information. Instructional activities noted in the case studies, such as having students attempt to model the observed phenomena, are an example of attempting to have students build from their previous learning. The implication is that cognitive conflict strategies should be coupled with educational materials that provide instructional scaffolding, not only exposing misconceptions but also drawing on and building from students' existing knowledge. In some cases, researchers suggest that significant work must be done before students are able to internalize concepts, including building the necessary background schema and threshold understanding before new concepts may be understood.[14, 59–61] Not all misconceptions are identical or of equal importance, and that different types of misconceptions call for different responses. Consistent with this, our own case studies show that the impact of cognitive conflict studies, both short term and long term, varied significantly by concept area.

Table 2 summarizes the approaches used in the case studies to overcome the typical limitations to the cognitive conflict approach.

TABLE 2
Practical Guidelines for Using Cognitive Conflict

To Do	How	Why
Assess prior knowledge	Use concept inventories or other pre-questions to establish students' level of understanding of foundational concepts	To avoid students missing conflict due to lack of prior knowledge
Prepare students to notice cognitive conflict	Present scenario of the discrepant event, have students discuss and/or write a prediction and their reasoning; consider using groupwork	Create conditions for intellectual engagement with the discrepant event
Present a discrepant event	When possible, use a student-run experiment to demonstrate the failure of common misconceptions; otherwise thought experiments (sharing results) also works	To create the cognitive conflict
Promote knowledge building	Peer discussion, writing, problem solving, modeling with explicit reference to what was learned in the discrepant event and how it was different from what was predicted	To solidify understanding
Recognize that conceptual change isn't instantaneous	Engage with the same concept more than once, at spaced-intervals; help students understand that learning takes time and involves making mistakes. Show that useful knowledge is not a collection of facts but involves connecting of underlying ideas.	To promote more lasting conceptual change

CONCLUSIONS AND RECOMMENDATIONS

Taken as a whole, an analysis of the classical change model suggests that early discussions of cognitive conflict found in the literature might have implied a model for change that was both too narrow and that promised too much. In the decades since the classical approach was formulated, researchers have tried to balance this by setting more realistic expectations and by emphasizing the complexity of the learning process and its dependence on several factors. Duit,[62] for example, calls for multidimensional approaches that consider epistemological, ontological and affective factors in the learning process. Similar suggestions for taking a more holistic view can be found in much of the literature. Our own case studies sought to adopt many of these suggestions for practical action, summarized in Table 2. None of the criticisms of the classical model imply, however, that cognitive conflict isn't a potentially powerful tool for promoting conceptual change. As Limon[12] notes, "cognitive conflict is a first step for any change or restructuring of students' beliefs, concepts or ideas." However, it is only a first step and our summary of the literature points out many situations in which approaches built upon cognitive conflict can fail. This recognition can help us understand the seemingly conflicting results on the effectiveness of cognitive conflict strategies found in the literature and in some of our own case studies.

Perhaps more importantly, the analysis highlights practical suggestions for instructors planning to use strategies that employ cognitive conflict to promote conceptual change. As with all instruction, characteristics of the learner—both cognitive characteristics such as prior knowledge and affective characteristics such as motivation—need to be taken into account. Secondly, cognitive conflict strategies are likely to be more effective when instructors view conflict as a "first step" for producing conceptual change and recognize that scaffolding—both intellectual and emotional—must be provided to help student build the desired understanding once they see the need for change. While much of literature emphasizes the tension between conceptual change strategies that confront rather than build on students' existing knowledge, this is in some ways a false dichotomy. Instruction may be most effective when both elements are integrated into a holistic approach, using conflict to motivate change and then transitioning to instruction that builds on and extends students' existing knowledge. Finally, informed instructional strategies that recognize key nuances—such as understanding that it is the nature of peer interactions rather than simply putting students in groups that promotes learning or that different types of misconceptions require different responses—are more likely to be effective.

All this notwithstanding, the results produced by the classical change approach as employed in these two engineering case studies are, on balance, quite encouraging. These results, along with a broader literature on the positive impact of the classical change strategy in the science education literature, illustrate that the classical change model need not be discounted simply because its initial conception was in many ways too narrow and too ambitious. Cognitive conflict strategies as employed in each of the two cases demonstrated significant student learning gains that were consistently superior to those found in traditional instruction and generally superior to commonly recommended strategies such as the use of analogy or active learning. While the evidence presented here is too limited to make broad conclusions about the relative effectiveness of different active learning strategies for promoting conceptual learning, it is clear that the classical approach is an effective tool that can be usefully employed by engineering educators in core engineering courses.

ACKNOWLEDGEMENTS

This project was funded in part by the U.S. National Science Foundation through grants DUE#1821405, DUE#1821439, DUE#1821638. The opinions are those of the authors and do not necessarily represent the National Science Foundation. IBLAs are available online through the AIChE Concept Warehouse, https://jimi.cbee.oregonstate.edu/concept_warehouse/.

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