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Proposing a Model of Conceptual Understanding of Equilibrium to Inform Interdisciplinary and Integrated Curricula

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Abstract

This paper describes a model of conceptual understanding of equilibrium as a result of a synthesis of literature across multiple domains. The proposed model incorporates aspects of conceptual change theories and evidence from literature regarding how students understand the concept of equilibrium in domains related to engineering. Specifically, this model suggests that students' conceptions of equilibrium are similar across disciplines and that a generalized approach may be taken to encourage meaningful understanding. It is the authors' intention that this model may provide a framework upon which interdisciplinary or integrated engineering curricula with a focus on equilibrium as a central focus can be developed.

Introduction

Interdisciplinary and integrated curricula are becoming more popular in undergraduate engineering education. One recurrent theme among integrated curricula is a focus on students developing an understanding of the engineering sciences as a complex system that involve fundamental sciences, modeling, and problem-solving. Interdisciplinarity in engineering education requires that students be able to integrate concepts and strategies from multiple perspectives in order to solve a given problem. However, students often struggle with transfer of similar engineering concepts across disciplines. Integrated curricula stress meaningful learning, in which learners attach meaning to the concepts covered, and concept formation, in which learners organize ideas and information to formulate new ideas and concepts that are consistent with a scientific worldview. Research into how students learn under these conditions may inform instructional practices of interdisciplinary and integrated curricula.

Equilibrium has been identified as a difficult concept in Mechanics, Thermodynamics, Chemistry, Economics, and other scientific disciplines that are incorporated into the engineering sciences. Additionally, understanding the limits of equilibrium is crucial to defining dimensions and boundaries of engineering problems. Students at the undergraduate level have been shown to hold many common misconceptions regarding equilibrium that may inhibit their overall learning of engineering sciences. These misconceptions often take form as incomplete, incoherent sets of context-specific ideas, however, an underlying misconception of equilibrium as a terminating event can be found in literature across multiple disciplines.

Although students enter engineering classrooms with a wide variety of prior knowledge, training, and experiences, they often undergo similar difficulties in constructing a scientifically accurate understanding of physical phenomena. Using conceptual change as a theoretical framework and the described model of conceptual understanding of equilibrium, implications may be drawn for instruction that supports the learning of equilibrium across multiple contexts and disciplines.

While theories of conceptual change may vary, aspects of these theories may be useful in understanding how students acquire conceptual understanding of equilibrium and educational conditions that promote conceptual change in this area.

This paper focuses on equilibrium as a core concept of the engineering sciences. Through analysis of research in multiple domains, a synthesized model of conceptual understanding of equilibrium has been developed. In this model, students may progress from a simplified, concrete view of equilibrium as a terminating event towards a more scientific understanding of equilibrium as a conditional model of physical phenomena that is functional for analysis at the engineering scale. This model expressly describes the epistemological framework of equilibrium within engineering knowledge, both in students' misconceptions and in an agreed-upon scientific worldview.

Interdisciplinary & Integrated Curricula

Research-based engineering education innovations have had substantial influence on first-year and capstone engineering courses in the form of first-year and interdisciplinary design experiences[1]. In light of this, there is a growing interest in potential innovation for the middle-years of engineering curricula, which usually focus on disciplinary engineering sciences that are deemed necessary for professional preparation. This factor, as well as an increased focus on interdisciplinary education has spurred the development of integrated curriculum for engineering education[2]. Integrated curricula allow students to engage in systems thinking as they integrate knowledge across domains[3]. By nature of an integrated approach, students may find motivation to engage in meaningful learning as engineering concepts are explicitly tied to multiple disciplines and non-engineering subjects[4]. Additionally, studies have indicated that students perform better on standardized tests when presented with engineering sciences in an integrated manner as opposed to traditional course sequences[4-5]. Most importantly to this paper, integrated curricula stress meaningful learning, in which learners attach meaning to the concepts covered, and concept formation, in which learners organize ideas and information to formulate new ideas and concepts that are consistent with a scientific worldview [4].

Conceptual Change

Conceptual change is a proposed theory that describes how learners acquire new knowledge and a scientific worldview by assimilating new information into existing cognitive structures in addition to accommodating new information through radical changes to cognitive structures or replacing existing cognitive structures with new frameworks[6]. Alternately, conceptual change may be cast as the ability to broaden one's understanding of concepts to accept multiple perspectives and understand how they relate to different contexts of applicability[7]. Characteristics of conceptual change pertaining to physical phenomena are unique in that individuals hold vast preconceptions of the physical world due to their situation within it. "In dealing with the physical world, humans gradually acquire an elaborate sense of mechanism - a sense of how things work, what sorts of events are necessary, likely, possible or impossible [8]".

Within science education research (particularly physics) extensive work in labeling alternative conceptions, naive conceptions, preconceptions, misconceptions, etc.. provide evidence upon which a specific model of conceptual change may be established to explain how students learn the concept of equilibrium.

The main tension in research surrounding the nature of novice or naive concepts is whether they exist as "knowledge-in-pieces" or "theory-like". "On the one hand, naive ideas have been described as coherent, systematic, or even theory-like - similar enough to scientists' carefully laid out and systematic *theories* to deserve the same descriptive term. On the other hand, naive ideas have also been described as many, diverse, "fragmented," and displaying limited integration or coherence[9]." diSessa presents knowledge in pieces as "phenomenological primitives" constituted of elements of knowledge originating from specific contextual experiences[8]. These "p-prims" are seen as small elements among a large collection, and often not applied in any consistent manner across contexts. Similarly, Minstrell identified "facets" of understanding that were used to describe student thinking as it was seen or heard in the classroom and represent individual pieces of students' knowledge or strategies of reasoning[10].

Vosniadou argues that novice conceptions cannot be viewed as distinct elements because they are tied to ontological and epistemological presuppositions that provide an explanatory basis for their existence, and that the difference between novice understanding and expert understanding is that novices are not aware of the underlying framework supporting their preconceptions[11]. "The importance of the assumption that early knowledge is organized in the form of naive theories lies in the fact that theory-like structures are generative. As such, they make it possible for children to formulate explanations and predictions and to deal with unfamiliar problems, thus enabling them to make sense of everyday phenomena. As mentioned above, naive theories are very different from scientific theories. They are not well formed, they are not explicit, they are not socially shared, and they are not accompanied by metaconceptual awareness[7]." As a proponent for a knowledge-in-pieces structure, diSessa argues that coherent models fail because they cannot be assessed[9].

The following model of learning equilibrium as conceptual change implements aspects of both "knowledge in pieces" and "theory-like" frameworks for conceptual change. Similar to what diSessa argues, assessment is suited to measuring how students' understand pieces of information. Much of the literature used to provide evidence of equilibrium as a difficult concept across domains rely on a knowledge-in-pieces structure to isolate and understand how students' misconceived specific concepts, whether the concept is equilibrium itself or a related concept. However, the learning process described in the following model relies heavily on a theory-like framework of conceptual change including knowledge or attitudes external, yet required for conceptual understanding of equilibrium. Specifically, the model addresses the underlying epistemological and ontological status of equilibrium within engineering knowledge.

Model of Learning Equilibrium as Conceptual Change

Equilibrium has been identified as a difficult concept in Mechanics, Chemistry, Thermodynamics, and other scientific disciplines that are incorporated in to the engineering sciences[12-14]. "There seems to be no topic in freshman chemistry that presents more difficulties to students than chemical equilibrium. After trying for over 30 years to give clear answers to their questions, I have come to have a great deal of sympathy with them, realising that the subject is inherently a difficult one (Hildebrand, 1946, p.589) as cited in [15]." And yet, understanding the limits of equilibrium is crucial to defining the dimensions and boundaries of an engineering problem[16].

Students often use previous physical experiences to understand equilibrium for both macro- and micro-level phenomena and tend to hold a simplified view of equilibrium as a terminating event in which nothing moves. As students encounter equilibrium in courses, they tend to rely on procedural knowledge to "solve the problem", without recognizing the relationships between equilibrium as a concept and the functional, representational models used in engineering. *Students may experience conceptual change towards a more scientific understanding of equilibrium through social learning experiences in context that explicitly analyze the epistemology of equilibrium as a macro-level model and allow students the opportunity to reflect upon their own metaconceptual awareness.*

Novices and experts hold very different beliefs about the role of theories and scientific models. Studies have shown that when students hold beliefs that knowledge is certain, unstable and dictated by authority, conceptual change is negatively affected [17-18]. "Epistemic beliefs can have both direct and indirect influences on conceptual change... for example, beliefs in simple, stable, certain knowledge can prevent individuals from being open to new information that questions some of their basic assumptions, while on the contrary, individuals who believe that knowledge is complex, uncertain and constantly evolving may be willing to open up the grammatical space and allow new paradigms or theories to be seriously entertained [7]." In assigning equilibrium the epistemic framework of a model, there are two assumptions that should be brought to light: "(a) people interpret their experiences using models; and (b) these models consist of conceptual systems that are expressed using a variety of interacting media (concrete materials, written symbols, spoken language) for constructing, describing, explaining, manipulating, predicting or controlling systems that occur in the world [19]." Although not often explicitly addressed in instruction, equilibrium serves as a macro-level model of micro-level phenomena that is useful for analysis. By highlighting the nature of engineering knowledge as a functional model of physical phenomena, students may develop epistemic beliefs that allow for complexity in their understanding of the physical world [20]. Figure 1 presents a concept map that displays a possible way of organizing the concept of equilibrium within an epistemic framework. The figure describes various models and representations used to understand the concept of equilibrium with direct connection to the underlying assumptions used when dealing with those models.

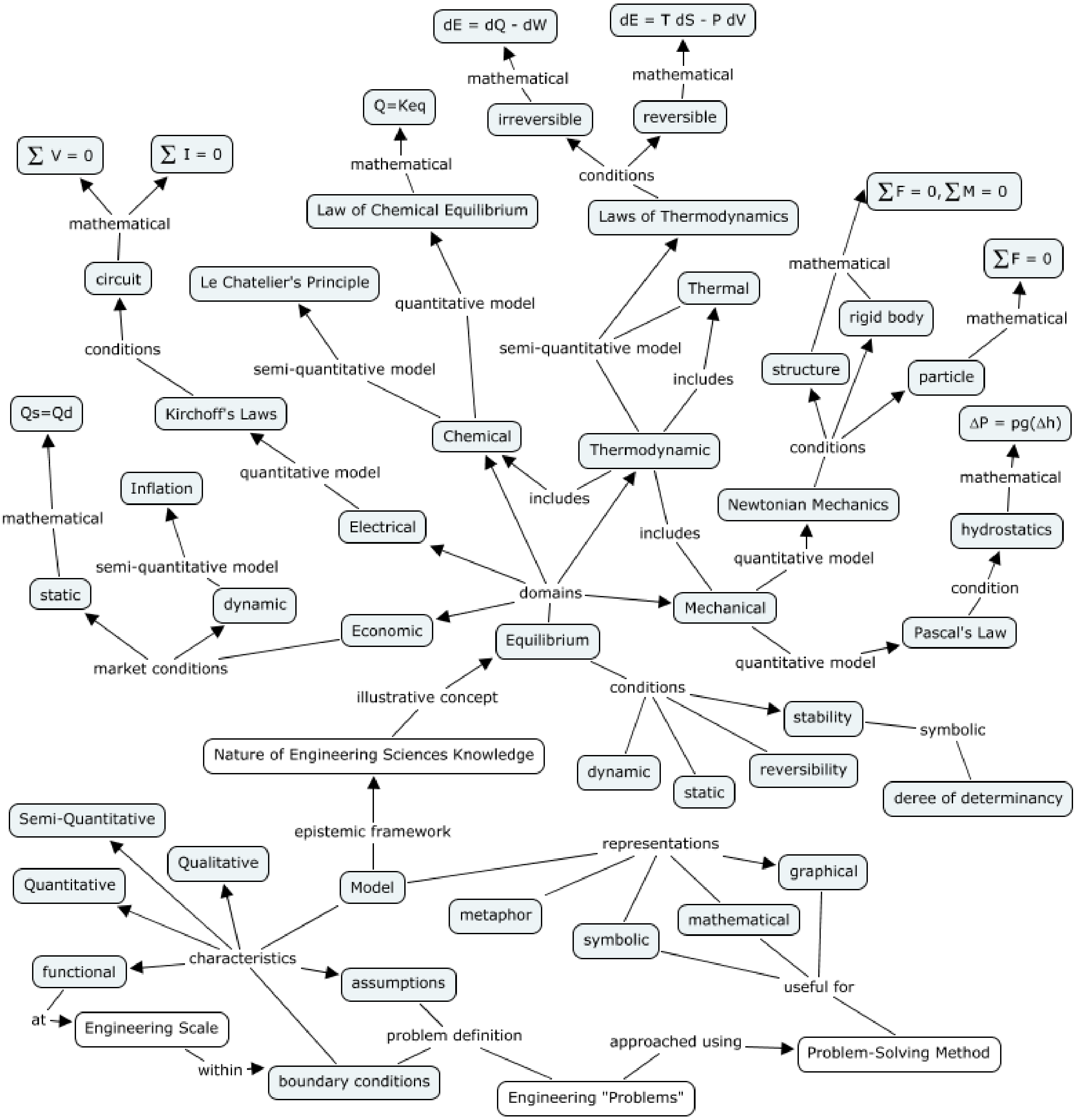

Figure 1. Concept Map of Equilibrium with Epistemic Framework

Compounding the complexity of conceptual understanding, Chi has shown that in addition to epistemological considerations, the ontology of concepts may influence the difficulty in understanding certain concepts and why misconceptions may be resilient [21]. Although not specifically described as a "theory-like" approach to conceptual change, Chi proposes that difficult concepts, or concepts that are resistant to change are often due to an incorrect categorization of knowledge. An ontological approach to conceptual understanding groups concepts into objects and processes, with further classification of processes into those that are sequential, or follow a causal behavior model, and those that are emergent, or processes that emerge from complex interactions[22]. In this framework, concepts belong to a type of categorization, for example students may classify physical phenomena as existing within a "object"-like state as opposed to a "process"-like state and would experience greater difficulty in experiencing conceptual change when having to reconcile a change in ontological state [21, 23]. Conceptual change is easier with concepts that have a similar ontological status, ie object or process. When misconceptions incorrectly categorize the ontology of a concept, the misconception will be difficult to change and may persist.

In the case of equilibrium, research has shown that students have a tendency to view equilibrium as a terminating event. As an example from physical systems, students interpret that forces may act on a body until it reaches equilibrium, at which point the body stops moving[14]. Also, students tend to make analogies between physical systems in understanding chemical systems: students often fail to understand the dynamic nature of chemical equilibrium, and instead liken it to balanced forces as one may encounter in statics[15, 24]. Again, students view equilibrium as an endpoint. In an example wherein students describe the process of diffusion, a common misconception is that dye molecules spread out only until the state of “equilibrium”, then they stop spreading – when in fact, the molecules will continue to act and interact even after equilibrium is reached[22].

In contrast to students' common misconception of equilibrium as a terminating event, equilibrium may be presented as an emergent process which can be described as having "no beginning or ending, no progression, uniform magnitude, simultaneous, ongoing, steady state, and equilibrium... There is no characteristic pattern over time and space, because the process is uniform and simultaneous everywhere[25]." Students that are guided towards models of equilibrium that include random, simultaneous, uniform activities may better develop a worldview that is consistent with equilibrium as a conditional model of physical phenomena[12].

Implications for Practice

Considering that a goal of engineering education is to guide students from a concrete, absolute mindset to one that can accommodate the complex nature of modern engineering problems, it seems logical that engineering science instruction should steer away from an absolutist framework and engage students in understanding the nature of engineering knowledge. The proposed model of learning equilibrium as conceptual change suggests that instruction should include opportunities for students to knowingly identify equilibrium as a model, what it means for a concept to be thought of as a model, and how that model can be understood and applied in a variety of disciplinary contexts. Although focusing specifically on the concept of equilibrium, the model of learning as described is grounded by the need for students to understand the nature of engineering knowledge as a functional, conditional model of physical phenomena.

Research findings have shown that students learn by fitting new information into existing cognitive structures and are unlikely to learn if the information has few apparent connections to what they already know & believe[26]. Recommendations for instruction based on this model suggest that students should be led to understand the nature of engineering knowledge by explicitly challenging what they already think about epistemologies of engineering based on prior knowledge and experience and using the concept of equilibrium as a means of building or altering those preexisting cognitive structures.

In addition to explicitly addressing the epistemic framework of the equilibrium as a concept, conceptual learning also requires attention to connections among concepts and students' metaconceptual understanding. Students' understanding of equilibrium often takes form as an incomplete, incoherent set of context-specific ideas[13]. In the case of statics, students often do not apply both elements (force and moment) of the applicable engineering principle consistently[14, 27]. Through instructional strategies that explicitly draw out connections between concepts, students may form more cohesive and organized theoretical models of equilibrium[13].

However, learners are often unaware of the changing nature of their beliefs and lack metaconceptual awareness[28]. This lack of metaconceptual awareness can lead to the develop of synthetic models of physical phenomena in which students change some, but not all of their beliefs regarding a concept. In order to avoid the construction of such synthetic models, students must become aware of the inconsistencies between their naive theories and the scientific ones. "In other words, instruction-induced conceptual change requires not only the restructuring of students' naive theories but also the restructuring of their modes of learning and the creation of metaconceptual awareness and intentionality[28]".

Conclusion

The proposed model of learning equilibrium as conceptual change can be concisely stated as, s*tudents may experience conceptual change towards a more scientific understanding of equilibrium through social learning experiences in context, that explicitly analyze the epistemology of equilibrium as a model and allow students the opportunity to reflect upon their own metaconceptual awareness.*

Engineers rely on conceptual understanding to mediate their interactions with the material world, and as such the construction of conceptual knowledge is a key factor in developing engineering expertise [29]. The engineering sciences provide rich domain-specific conceptual knowledge bases and principles for understanding the constraints of physical phenomena within the material world. Engineering education should strive for learning experiences that enable meaning conceptual understanding of the engineering sciences and the production of engineers that hold a worldview of physical phenomena consistent with a scientific mindset.

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