Conceptual Change and Understanding in Engineering Education

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Introduction

In the study of science, technology, engineering and mathematics education there is a tradition of evidence showing that students – despite their abundant procedural knowledge and computational skills – lack understanding of fundamental physical phenomena. Students can be academically successful without internalizing the meaning of the problems and calculations they complete. For example, after an introductory physics course most students will be familiar with Newton's second law relating net force to acceleration, and will be able to apply it successfully in homework and exam problems. Research has found however[1, 2], that when asked to describe simple kinematics concepts, many students relate net force to velocity, instead of acceleration.

The disjunction between students' procedural conceptual knowledge was first noted in Halloun and Hestenes' work with their Force Concept Inventory (FCI). The FCI is a series of multiple-choice, qualitative questions that require students to make simple predictions (e.g. predicting where an object will go from a depiction of the forces acting on it) or judgments (e.g. identifying the acceleration of a thrown object at the peak of its trajectory). The average score on the FCI prior to instruction was 27%, and was shown to not change significantly after instruction[1, 2]. A number of similar assessments have been developed in engineering-related fields including thermodynamics, materials science, dynamics and statics[3, 4], with the same general findings: students' explanations of fundamental phenomena are often different than experts, but show some commonality with other students' explanations.

A logical research agenda arising from this finding is to investigate why some forms of learning (i.e. conceptual understanding) are so much more difficult than other forms (i.e. procedural knowledge). In Halloun and Hestenes' work, and most subsequent studies, the pervasiveness and persistence of student conceptual difficulties was explained by the constructivist assumption that every student brings a "common sense"[5] understanding of the world to the study of physics. This means that learning requires changing a students' knowledge in addition to adding to it. During the normal course of life people explain the world around them in terms of the informal observations they make. All students who enter an introductory physics course have experienced gravity, acceleration and magnetism, and have developed a way of explaining their experiences. Most students have not developed equations and performed calculations based on their experiences, so procedural knowledge can be gained without changing any existing understandings. Halloun and Hestenes found, however, that in many cases common experiences lead to incorrect generalizations about the world. Newton's first law, for example, implies that objects in motion will naturally stay in motion until something stops them. This is in direct conflict with everyday experiences in which effort is always required to keep an object in motion. The difficult process of learning new material that contradicts existing knowledge and ways of thinking is called conceptual change.

The field of research that has developed around questions conceptual change has not been broadly utilized in engineering education research. The purpose of this paper is to present the two leading theories of conceptual change, examples of current research in this area, and how they can be applied to engineering teaching and learning.

Why Does Conceptual Change Matter?

It is worth briefly presenting the argument for considering conceptual change in engineering education research. Although students' scores on concept inventories surprise many instructors, the implications of low conceptual understanding in engineering are not often discussed. In the highly regulated apprenticeship system of engineering, graduates who are adept at calculations may be all that is needed. While the complete arguments on both sides of this issue are too involved to include here (and most likely will require future research to truly illuminate), we would like to highlight two key components of conceptual understanding that make it particularly important for practicing engineers. First, conceptual understanding is the type of flexible, abstracted knowledge that has been shown to be transferable, whereas procedural knowledge often only be applied in the context in which it was learned[6]. This means that students who are not developing conceptual understanding may be severely limited in their ability to apply their knowledge as practicing engineers unless the context of the work is sufficiently similar to the context of the learning. Secondly, conceptual understanding is longer-lived than procedural knowledge by definition. This is basically another way of stating the consistent finding that students' conceptual understanding is resistant to change. This means, however, that once productive conceptual understanding is established, it will take concerted effort over time to change: it cannot simply be forgotten in the same way memorized procedures or facts can be.

Theoretical Approaches to Conceptual Change

This paper will discuss the theoretical approaches of Michelene Chi and Stella Vosniadou. These two theories were chosen because they have the most explicit implications for engineering, and because they are the most richly developed and empirically validated. These two theorists do not represent the range of conceptual change research approaches, however. There are two primary divisions in conceptual change research: pieces versus coherence, and individual versus social cognition. In the pieces-versus-coherence debate, the primary issue is how organized and interrelated naïve student knowledge is[7]. The pieces view is characterized by Andrea diSessa's theory that naïve student knowledge acts as a loosely connected network of thousands of experience-based beliefs, and that conceptual change is the process of organizing these beliefs into a hierarchical system[8]. Both Chi and Vosniadou's work considers naïve student knowledge to be more coherent in that it is already organized into a hierarchical system and that conceptual change is required when this system conflicts with new information. The individual versus social cognition debate is concerned with how best to define knowledge. Most researchers (including Vosniadou, Chi and diSessa) consider knowledge to reside within individuals. Proponents of situated cognition argue that because knowledge is always acquired, changed and assessed through social interactions, it is best to consider it as a social construct[9]. In this view, approaches that do not account for socially situated effects such as interviewer-interviewee interactions or resources are overly limited.

Vosniadou's Framework Theories

Stella Vosniadou's approach to conceptual change is based on the theories students use to explain the world prior to science education. She defines a theory as a "…a relatively coherent body of domain specific knowledge that is characterized by a distinct ontology and a causality and can give rise to prediction and explanation" [10]. These theories exist at different levels of specificity, but Vosniadou proposes that what she calls the "framework" level is the most important in conceptual change.

Framework theories are domain-specific applications of a person's ontological assumptions about the universe. These ontological assumptions are universally applied to all of a person's knowledge and learning endeavors, but they have somewhat different consequences when applied to different domains of human experience. For example, a person may assume that the universe is non-intentional and behaves only in accordance with objective laws. This assumption may find direct expression in the study of physics, but be relatively unimportant in the study of sociology because people are understood as exercising agency, and therefore can't be assumed to be non-intentional.

The power of Vosniadou's framework theories is that they can be used to explain why some types of learning are more difficult than others. As the level of abstractness increases the learning processes become more difficult and lengthy due to the relative strength of the convictions and the students' own unawareness of them [11]. In this use, the word "abstractness" refers to the generality of the knowledge's application, or its inductive distance from experiences and observations. The strength of the convictions at each level of abstractness can be thought of as the breadth of their impacts if changed. Specific beliefs (e.g. that the rate of acceleration due to gravity is 32.2 feet per second per second) are the most easily changed, because they may require the modification of a few closely related beliefs.

Vosniadou states that belief revision is the easiest form of learning, and is therefore the dominant form during education[12]. In Vosniadou's approach, the learning of procedural knowledge could be thought of as the addition of new beliefs. The challenge for students, however, and the reason that conceptual understanding doesn't develop at the same rate as procedural knowledge, is that mental models are not often explicitly addressed in education. Students are told that force equals mass times acceleration, and they accept this as a new belief, but do not revise their mental models of motion in which forces result in movement which is characterized as velocity. When a student modifies or enriches their beliefs through education, but doesn't adjust their mental models or framework theories to accommodate the new beliefs, contradictions arise[13]. Vosniadou calls these contradictions "synthetic models," in that they are an artificially created hybrid of a students' own beliefs and those presented during instruction. In a description of children's conceptions of the shape of the earth[12], Vosniadou visually represented three synthetic models in which children had combined their experience of a flat earth with aspects of the spherical earth described in their education. These models include a "dual earth" model, in which there is a flat earth that people walk on and a spherical one in space, and a "hollow earth" model in which the earth is like a spherical fishbowl partially filled with soil that creates a flat surface for people to stand on. Synthetic models are problematic for students because they limit the explanatory and predictive power of their understanding. Synthetic models are key to understanding why it is more difficult to acquire conceptual understanding. Vosniadou writes, "[w]e argue that many science concepts are difficult to learn because they are embedded within scientific framework that violate fundamental principles of the naïve, framework theory of physics within which everyday physics concepts are subsumed" [12].

Chi's Types of Learning

Michelene Chi's describes three types of learning that are of key importance in science education: belief revision, mental model transformation and categorical shift [14]. Chi states that belief revision is relatively simple, even when new knowledge is in contradiction to students' existing beliefs [14]. Similarly, mental model transformation can be accomplished by direct presentation of contradictory information. Chi states that "…the accumulation of numerous belief revisions eventually result[s] in the transformation of a student's flawed mental model to the correct model…by-and-large"[14].

The truly difficult type of learning, and the process that Chi theorizes accounts for student difficulty in developing conceptual understanding, is what Chi calls categorical shift[15]. The categories referred to in the phrase "categorical shift" are most easily understood in terms of the cognitive and perceptual processes they relate to. Piaget, a seminal theorist in educational psychology hypothesized that in order to efficiently interact with the amazing variety of objects humans experience, a process of categorization and recognition is used[16]. Common life experience will support the hypothesis humans usually relate to objects based on previous interactions with similar objects. Although new styles of chair are designed each year, most people are able to very quickly identify these objects as chairs, and use their previous experiences with chairs to determine what to do with the models. This remarkable efficiency and flexibility is due to the process of categorization[17]. A categorical shift, then, is required when a learner miscategorizes an object.

Chi states that the persistent difficulty of developing conceptual understanding is due to the difficult in creating and revising categories. In particular, learning in science is hampered by the presence of two persistent misconceptions: the miscategorization of processes as substances, and the lack of a category for emergent processes[14]. Chi has found that many students think of heat as a substance that flows, while physicists describe heat as a process of energy transfer. A student, for example, would explain that opening a window on a cool day would cool a room because the heat can leave the room, but a physicist's explanation would include the transfer of energy between air in the room and the air outside. This miscategorization cannot be addressed through belief revision[18]. Furthermore, the categorization of heat as a substance actually interferes with belief revision[19]. Student difficulty in learning about heat is exacerbated by the fact that it is an emergent process. Emergent processes are those in which easily observed phenomena are the result of non-directional, random and often unobserved interactions, and are defined in contrast to direct processes in which goal-driven agents work sequentially in a visible causal chain. A common example of an emergent process is the tendency of flocks of migrating birds to fly in V-shaped formations. This is currently understood as an emergent process in which each bird reacts independently to their sensations of wind resistance. This is not a direct process, because the birds are not trying to form a V, and are therefore not basing their position on the positions of other birds. Similarly, heat is an emergent process because the energy transfer occurs due to the relative probabilities of high energy and lower energy molecules interacting; if it were a direct process, the energy transfer would be due to an observable macro-scale phenomenon like a temperature gradient. Chi proposes that most students do not possess an ontological category for emergent processes, and therefore classify all processes as direct.

As explained above, cognitive categories are used to interpret new experiences, including new information presented during instruction. This means when a student miscategorizes heat as a substance, everything they learn about heat will be interpreted to fit within the category of substance, and information that contradicts this or does not fit within the category will be discarded or changed[19]. For example, because heat is a process it can be said to have a duration, but coffee, which is a substance, cannot. A student who hears statements referring to "how long the heat lasts" will interpret this statement to mean "how long it takes for the heat to flow away" just as they would when hearing a similar statement about coffee. A similar statement about brewing coffee, something which is unproblematically categorized as a process, will be taken to refer to the duration of the process. In order to develop conceptual understanding of electricity or heat, therefore, students have to become aware of the need for recategorization before even beginning the difficult process. Chi states that developing awareness of when conceptual change is necessary may be the most important barrier to conceptual change. She writes, "[b]ecause students are able to generate predictable responses to questions and systematic explanations of phenomena, they don't notice that their model is incorrect"[19].

Implications for Engineering Education Practice

As argued above, engineers need conceptual understanding of physical phenomena in order to be flexible, efficient problem-solvers. Vosniadou and Chi's explanations of why and how that conceptual understanding can be so difficult to develop have some important implications for the practice of educating engineers.

Intention in Conceptual Change

First, the required revisions to framework theories and categorizations are difficult, and require intentional effort on the part of the learner[20]. Even given willing and motivated students, the educator must first make them aware of their abstract-level misconceptions. As Chi writes,

> The issue of awareness is easily addressed, in theory. All one would have to do is tell the student that he or she is wrong, and confront them with information and demonstrations that show the student's understanding to be flawed. One can even explain the correct principles to the students. However, in practice, this does not always lead to a more accurate, deeper understanding. As described earlier, one may directly refute or contradict a misconception with little or no effect.[19]

To clarify, when Chi writes "directly refute or contradict" it is in the context of her research based on students' understanding of written information. There is a proven methodology to encourage students to refute and contradict their own misconceptions. The first step is for research to identify the particular misconceptions in the field of study. Introductory physics is the most thoroughly investigated field in this way, and exhaustive taxonomies of misconceptions have been developed [5, 21]. While many physics concepts are applicable to engineering, little research has been done investigating common misconceptions in engineering-specific disciplines such as fluid mechanics or mechanics of materials[22].

Research in physics education has shown that once misconceptions have been identified they can be effectively addressed in the classroom by encouraging students' inductive reasoning[2, 23, 24]. Practically, students are presented with problems designed to elicit incorrect categorizations or framework theories and are encouraged to explain their own errors. This can be thought of as the instructor orchestrating experiences from which students can generalize correct scientific phenomena of the world. As stated above, common experiences in life can often lead to incorrect generalizations. Once these generalizations have been identified by research, problem sets, experiments and activities can be designed to create experiences that challenge the incorrect generalizations.

By forcing students to make predictions and explanations based on expected misconceptions instructors are able to make the abstract levels of students' knowledge more explicit. This process is primarily up to the student however; instructors can only go so far in helping students reflect on their own thinking. Chi has suggested that one aspect of science education should be explicit instruction in the metacognitive processes required for conceptual change[25]. Successful approaches have at least partially addressed this challenge by focusing on specific misconceptions, as opposed to the more systematic conceptual difficulties students are theorized to possess. In this way students can continue to work at the belief-level with which they are familiar, and only make minor conceptual changes during any given lesson. This is obviously less efficient than an ideal instructional method that would lead students to adjust their miscategorizations and framework theories holistically, but such a method has not yet been designed.

Emergent Processes and Synthetic Models in Engineering

Engineers in any discipline will have to understand and manage emergent processes. Examples range in scale and scope and include the evolution of stresses in members under bending, the function of microbial communities in bioremediation, structural failure of bridges, and traffic flow dynamics. In the absence of research identifying specific misconceptions in most domains of engineering, instructors could identify subjects of probable conceptual difficulty by identifying the emergent processes covered in their courses. As explained by Chi, students will first need to be taught about the category of emergent process before they can successfully categorize or recategorize processes as emergent. As in Chi's papers[14, 19], such instruction could leverage people's intuitive understanding of direct processes to explain emergent processes by emphasizing the divergence from direct processes.

The context-specific way in which science is taught in engineering may promote the creation of more synthetic models. For example, most engineering students take a course based on the analysis of static bodies. The beliefs accumulated and revised through this very specific application of Newtonian physics may are not likely to induce changes in the students' framework theories. These synthetic theories then serve to compartmentalize students' knowledge, because they create inappropriate contextual limitations. Students may develop conceptual understanding of free body diagrams in terms of trusses (a commonly used example in statics textbooks), but be unable to apply that understanding to the analysis of internal forces in structural members because each application is organized under its own synthetic framework theory. For educators, this provides an explanation of the commonly expressed frustration that students seem unable to apply knowledge across courses. It also provides a means of addressing that frustration because once synthetic models have been identified, they too can be elicited and contradicted in class. In this way, instructors will be able to move beyond ineffectually contradicting incorrect student beliefs and on to helping students address the sources of those beliefs.

Conclusion

A theoretical understanding of conceptual change has direct implications for the practice of engineering education. Vosniadou and Chi have developed clear means of characterizing students' previously developed conceptual knowledge, which will allow engineering educators to answer persistent questions about why certain concepts are more difficult to learn, and why students may seem to inappropriately compartmentalize their knowledge. In order to educate engineers who are capable of applying their fundamental understandings of science to diverse societal problems, educators need to be aware of the importance of this level of students' knowledge, and the role it plays in learning.

Bibliography

1. Hestenes, D., M. Wells, and G. Swackhamer, *Force Concept Inventory.* The Physics Teacher, 1992. **30**: p. 141-158.
2. Hake, R.R., Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. American Journal of Physics, 1998. **66**(1): p. 64-74.
3. Evans, D.L., et al. *Progress on Concept Inventory Assessment Tools*. in *Frontiers in Education*. 2003. Boulder, CO.
4. Foundation Coalition. *Concept Inventory Assessment Instruments*. [cited 2008 October 14, 2008]; Available from: http://www.foundationcoalition.org/home/keycomponents/concept/index.html.
5. Halloun, I.A. and D. Hestenes, *The initial knowledge state of college physics students.* American Journal of Physics, 1985. **53**(11): p. 1043-1048.
6. Bransford, J.D., A.L. Brown, and R.R. Cocking, eds. *How People Learn: Brain, Mind, Experience and School*. ed. N.R. Council. 2000, National Academy Press: Washington.
7. diSessa, A.A., *A bird's eye view of 'pieces' vs 'coherence' controversy*, in *Handbook of Conceptual Change Research*, S. Vosniadou, Editor. 2008, Erlbaum: Mahwah. p. 35-60.
8. diSessa, A.A., *Coherence versus fragmentation in the development of the concept of force.* Cognitive Science, 2004. **28**: p. 843-900.
9. Ivarsson, J., J. Schoultz, and R. Säljö, *Map reading versus mind reading: Revisiting children's understanding of the shape of the earth*, in *Reconsidering Conceptual Change: Issues in Theory and Practice*, M. Limón and L. Mason, Editors. 2002, Kluwer Academic Publishers: Dordrecth, The Netherlands. p. 77-99.
10. Vosniadou, S., Z. Vamvakoussi, and I. Skopeliti, *Conceptual change research: An introduction*, in *International Handbook of Research on Conceptual Change*, S. Vosniadou, Editor. 2008, Routledge: New York. p. 3-34.
11. Vosniadou, S., *Exploring the relationships between conceptual change and intentional learning*, in *Intentional Conceptual Change*, G.M. Sinatra and P.R. Pintrich, Editors. 2003, Lawrence Erlbaum Associates: Mahwah, NJ. p. 377-406.
12. Vosniadou, S., Z. Vamvakoussi, and I. Skopeliti, *The framework theory approach to the problem of conceptual change*, in *International Handbook of Research on Conceptual Change*, S. Vosniadou, Editor. 2008, Routledge: New York. p. 3-34.

13. Vosniadou, S., *The conceptual change approach and its reframing*, in *Reframing the Conceptual Change Approach in Learning and Instruction*, S. Vosniadou, A. Baltas, and Z. Vamvakoussi, Editors. 2007, Elsevier: Amsterdam. p. 1-15.
14. Chi, M.T.H., *Three types of conceptual change: Belief revision, mental model transformation and categorical shift*, in *International Handbook of Research on Conceptual Change*, S. Vosniadou, Editor. 2008, Routledge: New York. p. 61-82.
15. Chi, M.T.H., *Commonsense conceptions of emergent processes: Why some misconceptions are robust.* The Journal of the Learning Sciences, 2005. **14**(2): p. 161-199.
16. Piaget, J., *The Origins of Intelligence in Children*. the Norton Library. 1963, New York: International Universities.
17. Piaget, J., *Science of Education and the Psychology of the Child*. 1970, New York: Orion.
18. Chi, M.T.H., *Conceptual change within and across ontological categories: Examples from learning and discovery in science*, in *Cognitive models of science: Minnesota studies in the philosophy of science*, R. Giere, Editor. 1992, University of Minnesota Press: Minneapolis, MN. p. 129-186.
19. Chi, M.T.H. and R.D. Roscoe, *The processes and challenges of conceptual change*, in *Reconsidering Conceptual Change: Issues in Theory and Practice*, M. Limón and L. Mason, Editors. 2002, Kluwer Academic Publishers: Dordrecth, The Netherlands.
20. Sinatra, G.M. and P.R. Pintrich, *The role of intentions in conceptual change learning*, in *Intentional Conceptual Change*, G.M. Sinatra and P.R. Pintrich, Editors. 2003, Lawrence Erlbaum Associates: Mahwah, NJ.
21. McDermott, L.C., *Physics by Inquiry*. Vol. I & II. 1996, New York: John Wiley & Sons, Inc.
22. Streveler, R., et al., *Learning conceptual knowledge in the engineering sciences: Overview and future research directions.* Journal of Engineering Education, 2008. **97**(3).
23. Heron, P., et al., *Helping students develop an understanding of Archimedes' principle. II: Development of research-based instructional materials* American Journal of Physics, 2003. **71**(11).
24. Shaffer, P.S. and L.C. McDermott, *A research-based approach to improving student understanding of the vector nature of kinematical concepts.* American Journal of Physics, 2005. **73**(10): p. 921-931.
25. Slotta, J. and M.T.H. Chi, *Helping Students Understand Challenging Topics in Science Through Ontology Training.* Cognition and Instruction, 2006. **24**(2): p. 261-289.