Mayer, R. E. (2002). Understanding conceptual change: A commentary. In *Reconsidering conceptual change: Issues in theory and practice* (pp. 101-111). Dordrecht: Springer Netherlands.

UNDERSTANDING CONCEPTUAL CHANGE: A COMMENTARY

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Abstract In this essay, I compare and contrast four views of conceptual change--Vosniadou's *synthetic meaning* view, Chi and Roscoe's *misconception repair* view, diSessa's *knowledge-in-pieces* view, and Ivarsson, Schoultz, and Säljö's *sociocultural* view. In particular, I compare these four views in terms of what changes during conceptual change, who changes, how the change occurs, where the change takes place, the role of prior knowledge, and whether their is research evidence. As a conclusion, I offer a proposal for reconciling alternative views of conceptual change.

1. INTRODUCTION

How does a learner come to understand how force and motion work, how the human respiratory system works, or how gravity keeps objects on the earth? In each case, the learner undergoes a process of conceptual change in which he or she builds a coherent mental representation capable of explaining the target phenomenon.

Conceptual change is the mechanism underlying meaningful learning. Conceptual change occurs when a learner moves from not understanding how something works to understanding it. For decades scholars have recognized that conceptual change is at the heart of meaningful learning. Over the years, conceptual change has been represented as a process of achieving structural insight, accommodative learning, understanding of relations, deep learning, or--more recently--mental model building (Mayer, 2000).

Conceptual change has long been recognized as a fundamental aspect of science learning, and as a key process in learning in other domains. If scholars could understand how conceptual change works they would make important contributions both to learning theory and to educational practice. Throughout the first half of the 20th century researchers sought to build general theories of learning that could account for all forms of learning, but by mid-century it became clear that such efforts had failed (Mayer, 2001). Instead, today scholars focus on domain-specific theories of learning, such as trying to understand how people learn how something works or how to carry out a given procedure. Gone are the days when grand theories of learning dominated psychology and education, replaced today with more focused

M. Limón & L. Mason (Eds.), *Reconsidering Conceptual Change. Issues in Theory and Practice*, 101-111.

and modest theories of learning. The search for a research-based theory of conceptual change represents a major component in this focused strategy.

My assignment in this piece is to compare and contrast four views of conceptual change: Vosniadou's (this volume) *synthetic meaning* view, Chi and Roscoe's (this volume) *misconception repair* view, diSessa's (this volume) *knowledge-in-pieces* view, and Ivarsson, Schoultz, and Säljö's (this volume) *sociocultural* view. In each of four respective sections, I analyze the views in terms of what changes during conceptual change, who changes, how the change occurs, where the change takes place, the role of prior knowledge, and whether their is research evidence. Finally, in the last section, I attempt to synthesize a vision of conceptual change based on the ideas in these four views.

2. VOSNIADOU'S SYNTHETIC MEANING VIEW OF CONCEPTUAL CHANGE: CHANGE AS SYNTHESIS

What changes? In Vosniadou's theory, the learner seeks to builds a coherent explanatory framework (or mental model) of how some system works. In short, what changes is the learner's mental model.

Who changes? In Vosniadou's theory, learners are synthesizers who attempt to reconcile inconsistent models of how something works. The learner is a model builder who creates conflict by acquiring inconsistent new knowledge but who seeks to build internally consistent models.

How does change occur? Learners build a mental model by integrating new material from science instruction with their existing explanatory frameworks: "Information received through instruction seems to become assimilated to the initial explanatory framework creating synthetic or internally inconsistent models." Conceptual change begins with the learner's existing explanatory framework, that is, a naive theory of how something works based on personal experience: "Children construct a narrow but coherent explanatory framework that guides the process of acquiring knowledge about the physical world from early on." The next step in conceptual change occurs when learners are exposed to science instruction that is inconsistent with their existing mental representations; as they assimilate this new knowledge with existing mental representations they form synthetic meanings that lack coherence and stability. The final step is to resolve the internal inconsistencies, so "conceptual change occurs from the need to solve internal inconsistencies." This process of resolving internal inconsistencies in the learner's knowledge is a gradual one which can result in a progression of mental models. Rather than involving sudden replacement of misconceptions, conceptual change involves assimilating new scientific knowledge to existing explanatory frameworks, thereby creating internal inconsistencies that must be gradually reconciled. Rather than involving the process of organizing isolated knowledge fragments, conceptual change is a process of assimilating knowledge to existing structures, which must then be reorganized.

Where does change occur? Vosniadou presents a cognitive account of conceptual change in which the changes occur within the learner's mind.

What is role of prior knowledge in conceptual change? In Vosniadou's view of conceptual change, prior knowledge is both an obstacle for change--because it must be revised--and a vehicle for change--because new conflicting knowledge is assimilated to it.

Is there research evidence? In an exemplary study, kindergarteners, 4th graders, 6th graders, and 9th graders were asked in an interview to answer a series of questions about force. For example, in one question they were shown a drawing of a stone standing on the ground and asked, "Is there a force exerted on the stone? Why?" For most of the students, it was possible to classify their answers as consistent with one out of a small number of mental models of force. The most common model for kindergarteners was *internal force*, the idea that objects have internal force based on their weight or size. The internal force model is an example of an initial explanatory framework based on personal experience. The most common model for 4th graders was *internal and acquired force*, the idea that objects have internal force based on their weight or size, but there is also an acquired force within moving objects only. There is an internal inconsistency in the synthetic meaning of combining internal force and acquired force. The most common model for 6th graders was *acquired force*, the idea that there is an acquired force within moving objects only. The reliance on acquired force, which is another explanatory framework, can be seen as an attempt to resolve the inconsistency inherent in the internal and acquired force model. The most common model for 9th graders was *gravitational and other forces*, the idea that forces in objects come from gravity, from being pushed or pulled, and from moving. Students appear to be assimilating Newtonian concepts within their existing framework based on acquired force. By adding the force of gravity and the force of push/pull to the force of movement, learners create various synthetic meanings that eventually need to be resolved.

3. CHI AND ROSCOE'S MISCONCEPTION REPAIR VIEW OF CONCEPTUAL CHANGE: CHANGE AS REPLACEMENT

What changes? In Chi and Roscoe's view, the learner seeks to construct an accurate mental model of how something works. When mental models initially are based on incorrect conceptions (as in *naive knowledge*), these conceptions must be replaced: "All naive knowledge needs to be repaired in order to promote deep understanding." Thus, what changes is the learner's mental model and the conceptions from which it is built. In particular, a misconception is defined as a miscategorized concept, so what changes is the placement of a concept from an incorrect category to a correct category. The resulting mental model changes from being flawed to being correct.

Who changes? Learners are fixers who repair erroneous conceptions in their mental models. Learners engage in the repair process by recognizing misconceptions (i.e., miscategorized concepts) and creating or finding new categories into which the miscategorized concepts can be placed.

How does change occur? Conceptual change occurs when a learner identifies a faulty conception in his or her mental model, and repairs it. Learners begin with naive knowledge--or existing conceptions--that are often incorrect. Naive knowledge

can consistent of *preconceptions*, which easily can be revised or removed through instruction, and *misconceptions*, which are misunderstandings that persist even when confronted with focused instruction. In short, "cognitive change is the process of removing misconceptions." The mechanism by which misconceptions are repaired involves recategorizating a concept from an incorrect category to a correct category: "Misconceptions are, in fact, miscategorizations of concepts" so "conceptual change is merely a process of reassigning or shifting a miscategorized concept from one … category to another." To accomplish conceptual change, learners must become aware that they have miscategorized a concept and must invent or find an appropriate category to which it can be reassigned. Conceptual change means to change from a flawed (or incomplete) mental model to a correct mental model through assimilation (i.e., adding new pieces of knowledge) and revision (i.e., correcting pieces of knowledge). This is an incremental process--of changing many small pieces of knowledge--rather than a process of sudden accommodation.

Where does change occur? Conceptual change is a cognitive process that occurs within the learner's mind.

What is the role of prior knowledge in conceptual change? Prior knowledge--when it contains misconceptions--is an obstacle to conceptual change: "Naive knowledge ...often (but not always) impedes the learning of formal knowledge with deep understanding."

Is there research evidence? First, Chi and Roscoe describe previous research on 8th graders' preconceptions about how the human circulatory system works (Chi, 2000). Based on in-depth interviews, a collection of incorrect conceptions was identified (such as "all blood vessels have valves"). Then, students read a text about the human circulatory system and were interviewed again as a post-test. Many of the preconceptions that were addressed in the text were correctly revised on the post-test (such as "veins are the only vessels to have valves"), but those not addressed in the text were not correctly revised on the post-test. This research shows that some incorrect conceptions can be changed easily through instruction--namely, preconceptions.

The authors also describe a more recent study in which students read a text about the human circulatory system and explain to themselves what various sentences mean. Interviews with students show that the self-explanation process fosters incremental revisions of individual propositions about how the human circulatory system works, enabling students to change from a single loop model (in which only the heart is involved in pumping oxygen to the body) to a double-loop model (in which the lungs and heart are involved). This research shows that what appears to be a major conceptual change (from a single-loop to double-loop model) can be created by repairing individual pieces of knowledge about the circulatory system.

4. DISESSA'S KNOWLEDGE-IN-PIECES VIEW OF CONCEPTUAL CHANGE: CHANGE AS ORGANIZING

What changes? In diSessa's view--expressed in his chapter and elsewhere (diSessa, 2001)--the learner organizes many fragments of naive knowledge into a structured mental representation of complex system. Learning involves the construction of what diSessa calls a *complex knowledge system* (or *conceptual ecology*) consisting of a large number of different kinds of conceptual elements that are modified and combined in complex ways such as levels and subsystems. What changes, then, is the way that knowledge is organized--from fragmented to structured.

Who changes? Learners are knowledge organizers who strive to build connections among the diverse elements in their knowledge base.

How does change occur? The process of conceptual change relies on mentally reorganizing one's knowledge: "Conceptual change involves a large number of diverse kinds of knowledge organized and re-organized into complex systems." Learners begin with intuitive knowledge called *p-prims* (for *phenomenological primitives*)--small, simple, plentiful, natural-feeling pieces of knowledge used to help understand one's experience. For example, in intuitive physics, a p-prim is the idea that "induced motion just dies away", that is, an object in motion requires a force acting on it to stay in motion. However, in the course of conceptual change, p-prims are integrated into more complex explanatory systems. P-prims no longer function as isolated monolithic explanations but rather become part of a larger system. DiSessa notes that "many p-prims find useful places in the complex system" and might "come to be known as an effective special case of a scientific principle." Thus, the mechanism underlying conceptual change is not a simple process of deletion or replacement of p-prims, as in contrasting views of conceptual change, but rather a complex process of integration and reorganization.

Where does change occur? Conceptual change is a cognitive process that occurs in the learner's mind.

What is the role of prior knowledge in conceptual change? Prior knowledge--such as p-prims--form the basis for conceptual change. Prior knowledge enables conceptual change because conceptual change involves organizing existing pieces of knowledge.

Is there research evidence? The supporting empirical evidence for diSessa's argument comes from selected segments of the protocol of a structured clinical interview about physics problems with one child called J. However, diSessa correctly warns that "I don't intend to prove or demonstrate here."

5. IVARSSON, SCHOULTZ, AND SÄLJÖ'S SOCIOCULTURAL VIEW OF CONCEPTUAL CHANGE: CHANGE AS TOOL APPROPRIATION

What changes? In conceptual change, learners appropriate intellectual tools (i.e., agreed-upon concepts such as the concept of gravity) and physical tools (i.e., agreed-upon representations such as maps and globes). The authors claim that cognition is the use of tools, so conceptual change involves the development of tool-

using practices. Thus, what changes is the way that tools are used by learners in various contexts: "An important part of cognitive development is the gradual appropriation and/or mastery of mediational means."

Who changes? Learners are tool users in social context: "Mental functioning is irrevocably intertwined with a vast array of cultural tools" so it is not possible to study mental processes independently of cultural tools. Accordingly, conceptual change does not occur within individual minds. Rather the change occurs as an interaction between the learner, tools, and other people.

How does change occur? Conceptual change through the learner's participation in using intellectual tools (e.g., concepts) and physical tools (e.g., artefacts) within relevant social activities, or what Ivarsson, Schoultz, and Säljö call *collective cultural practices.* The authors state that "human cognition is socialized through participation in activities where tools are used for particular purposes" so there are "intimate links between cognition and the use of tools in situated practices." For example, in using a globe or a map to answer questions about whether it is possible to fall off the earth, a learner is using a physical tool--the globe or map--to reason. Conceptual change occurs through interacting with other people in situations requiring the use of intellectual and/or physical tools.

Where does change occur? Ivarsson, Schoultz, and Säljö challenge the "assumption that human mental functions are located in individuals." Taking a sociocultural perspective, human cognition takes place in a sociocultural context as an interactive process rather than a purely cognitive one.

What is the role of prior knowledge in conceptual change? In Ivarsson, Schoultz, and Säljö's view, prior knowledge is neither an obstacle nor a prerequisite for conceptual change. The learner begins without using appropriate tools and must learn to become a more effective tool user.

Is there research evidence? The major empirical evidence comes from structured interviews with children who are asked geographic questions such as whether it is possible for people to fall off the earth. When the children are allowed to use a world map (as a mediational tool) they display sophisticated reasoning about the nature of the earth. Such evidence supports the idea that human cognition is tool-dependent so that different kinds of reasoning occur when children have access to different kinds of tools. It therefore does not make sense to describe conceptual change as a progression of mental models, because students' mental models are influenced by the mediational tools they have available in any particular situation (such as maps).

6. RECONCILING COMPETING VIEWS OF CONCEPTUAL CHANGE

In this section, I attempt to reconcile the four competing views of conceptual change represented in these four chapters. For purposes of conciseness, I refer to the four chapters by their first or sole author's name--Vosniadou, Chi, diSessa, and Ivarsson, respectively. The four views are summarized in Table 1.

Which version of constructivism best characterizes conceptual change? My attempt at synthesis begins with a thorny problem: Three of the four chapters

(Vosniadou, Chi, and diSessa) grow out of a cognitive tradition of viewing conceptual change as a process of knowledge building whereas one of the chapters (Ivarsson) comes from a sociocultural tradition which the authors claim cannot be reconciled with the others: "Although it would be tempting to create syntheses between traditions, our preference would be to keep them apart." In spite of Ivarsson's us-versus-them view, I believe my efforts at synthesis are still warranted.

Ivarsson lays out the major thesis that cognition always occurs in social and cultural (or historical) context because cognition requires the use of appropriate cultural tools: "We cannot separate thought processes, say in the context of doing geometry or playing chess, from the conceptual tools that are applicable to such activities." "Cultural tools form an integrated part of cognitive processes. " "There is no sense…in assuming that there is a level of thinking that is pure." "Thinking is the use of tools." I fail to see how this thesis is inconsistent with the cognitive view that conceptual change involves knowledge construction. I agree that it is impossible to think in general; rather thinking is always about something ranging from how to solve a geometry problem to how to find the meaning of a text, that is, cognition always occurs in context. If knowledge is framed as a cultural tool, then the goal of research on conceptual change remains to determine how knowledge changes in learners. Following Vygotsky's theory, Ivarrson states that "learning and conceptual development could be seen as a process of internalisation by individuals of conceptual tools." This characterization of the conceptual change process appears to be consistent with a cognitive psychological perspective in which learning results in a change in the learner's knowledge. In short, I see room for reconciliation between Ivarsson's points and the cognitive psychology tradition.

Not all of Ivarsson's points appear easy to reconcile with the other views, especially the assertion that "concepts are not just mental entities that reside inside our heads, they are part of human social practices." However, read in the most optimistic way, this statement allows for cognitive representations--and hence the cognitive tradition--because it suggests one aspect of concepts is that they are mental entities that reside inside our heads. Further, the idea that concepts exist as part of social practices--that is, that knowledge must be used within certain situations--also does not seem to contradict the idea that people possess and use knowledge. Finally, the emphasis on language--particularly speech--as the major cognitive tool seems to exclude other forms mental representation such as visual imagery: "Thinking in this perspective is conceived as a kind of silent and private dialogue." However, even Ivarsson's examples using maps and globes show that representational systems used to support human cognitive activity can include visual imagery. Again, the use of representational tools to build knowledge is highly consistent with the cognitive tradition.

The most troubling aspect of Ivarsson's piece is the refusal to consider ways of synthesizing the cognitive and sociocultural approaches because of "conflicting assumptions about the nature of human cognition…that cannot be easily resolved by appealing to empirical data." What is wrong with insisting that "my *ism* is better than your *ism*"? In analyzing the various forms of constructivism, it is worthwhile to

Table 1. Four views of conceptual change

View	What is conceptual change?	What changes?	Who changes?	How does change occur?	Where does change occur?	What is prior knowledge?
Vosniadou's synthetic meaning	Change as synthesis	mental model (from incoherent to coherent)	Learners as synthesizers	gradual: adding new information from instruction to initial explanation and reorganizing conflicting representations into a scientific theory	mind	obstacle and vehicle
Chi & Roscoe's miconception repair	Change as replacement	mental model (from flawed to correct)	Learners as fixers	gradual: repairing incorrect conceptions	mind	obstacle
DiSessa's knowledge in pieces	Change as organizing	knowledge (from unstructured to structured)	Learners as organizers	gradual: organizing p-prims	mind	vehicle
Ivarsson et al's Sociocultural	Change as tool appropriation	tool use (from ineffective to effective)	Learners as tool users	gradual: appropriating and mastering mediated means through participation in cultural practices	society	neither

distinguish among cognitive constructivism, social constructivism, and radical constructivism (Mayer, 1997). In cognitive constructivism, the learners build knowledge in their minds. In social constructivism, this knowledge building process is guided by social interaction and takes place in a social context. In radical constructivism, there are no such things as knowledge representations in learner's minds; rather, knowledge exists only within a social context. Both cognitive constructivism and social constructivism are mutually compatible and allow for scientific testing; radical constructivism is not compatible with the others and does not appear to support a rigorous scientific approach. Instead, radical constructivism depends on a relativistic view in which all theories are equally valid, and in which scientific testing is obsolete. If Ivarsson's approach is cast as social constructivism, then synthesis with the other approaches is possible; however, if Ivarsson's approach is cast as radical constructivism, it is irreconcilable but it also relinquishes any claims of being scientific. My opinion is that a doctrine-based approach to the study of conceptual change is not likely to be productive. My assessment is supported by the 100-year history of failure of doctrine-based approaches to human learning (Mayer, 2001). During the last century scholars attempted to build grand theories of learning by arguing about which brand of behaviorism was best, comparable to today's arguments about which version of constructivism is best. In summary, my point is simple: The search for the perfect *ism* is not a fruitful path for our science. A doctrine-based approach to our science has been tried and it has failed. I urge scholars to take an issue-based approach in which we agree to try to understand how conceptual change works rather than to determine which *ism* is right.

What is conceptual change? The chapters I have reviewed offer thoughtful and insightful analyses of the mechanisms underlying conceptual change. I characterize the four competing views of conceptual change as synthesis, replacement, organizing, and tool appropriation. In each theory, conceptual change is a cognitive process in which the learner seeks to construct knowledge that is coherent and useful. In some, it is also a social process in which the learner comes to use the agreed-upon cognitive tools of one's culture.

What changes? In each of the theories, the learner's knowledge is the locus of conceptual change. The result is a mental representation that is organized and functional. In some, it is also a socially agreed-upon representation.

Who changes? In each of the theories, the learner is an active sense maker--conceived of as synthesizer, fixer, organizer, or tool user. The sense making process includes detecting and correcting inconsistencies in one's knowledge--as highlighted by Chi--as well as building coherent structures--as highlighted by Vosniadou and by diSessa.

How does change occur? In all of the theories, conceptual change is a gradual process of knowledge building. Specifying the mechanism underlying conceptual remains as the central challenge of research on conceptual change. Can all conceptual change be explained as replacing incorrect conceptions that form a larger mental model

(as suggested by Chi), as organizing one's prior experiences (as suggested by diSessa), as reorganizing one's old and new knowledge (as suggested by Vosniadou), or as becoming increasingly proficient in using cognitive tools (as suggested by Ivarsson)? In order to answer this question, the theories must be specified in more detail so that they can be subjected to rigorous scientific testing.

Where does change occur? Three of the four theories share a common goal of determining the mechanism by which conceptual change occurs in learners--Vosniadou's synthetic meaning, Chi's misconception repair, and diSessa's knowledge in pieces theories. In these three theories, conceptual change occurs in the learner's mind. Ivarsson's sociocultural theory emphasizes the idea that the change may be influenced by and is dependent upon the social and situational context. However, in my reconciliation, the human mind remains as the venue for change.

What is the role of prior knowledge in conceptual change? Prior knowledge is both an enabler of conceptual change--providing the building blocks out of which new knowledge structures are built--and an obstacle to conceptual change--when existing knowledge is incorrect but entrenched. DiSessa stresses the first aspect of prior knowledge and to varying extents Vosniadou and Chi stress the second aspect, but both aspects can be seen all theories.

Is there research evidence? Most of the research evidence comes from structured interviews in which students are asked to explain various scientific phenomenon--such as whether a resting object has a force exerted on it, how the human circulatory system works, whether heavier objects fall faster, and whether it is possible for a person to fall off the earth. In some cases, comparisons are made between children at various age levels (e.,g., Vosniadou) and in others the comparisons are made with children at various points in their learning about a topic (e.g., Chi). In my opinion, the field benefits from both cross-sectional and longitudinal studies. In some cases, the results are presented in quantitative form such as the percentage of students with each type of conception (e.g., Vosniadou and Chi) and in others the results are presented in qualitative, form as a segment of a transcript (e.g., diSessa and Ivarsson). In my opinion, the field benefits from both quantitative, and qualitative data. Quantitative data are useful for theory testing but may fail to capture the richness of authentic learning. For example, Vosniadou provides important statistics showing developmental changes in the kinds of conceptual models that children use for understanding force and motion; however, the data do not clarify exactly how the change occurs from one level of understanding to the next. In contrast, qualitative data can be useful in providing detail but may be less useful in theory testing. For example, diSessa shows how qualitative data provides a rich texture in which to better appreciate the complexity of conceptual change within individual learners; however, selected portions of transcript from a single learner are unlikely to meet the criteria for rigorous scientific testing of a theory of conceptual change. In my opinion, the best course of action is to include a variety of research methods that converge on the explication of conceptual change.

From my vantage point, the biggest challenge facing conceptual-change researchers is to specify testable theories and find empirical data to test them. Chi and Vosniadou provide exemplary research programs in which they offer detailed testable hypotheses concerning the nature of conceptual change supported by impressive amounts of both qualitative and quantitative data. Now, what is needed is to continue to specify detailed theories about the mechanisms of conceptual change and to create rigorous methodologies capable of generating high-quality data to test them. In short, the two most challenging ingredients for research on conceptual change are *mechanisms* and *methodologies*--that is, mechanisms embodied in detailed theories and methodologies that generate relevant data for testing the theories.

Finally, the ultimate challenge is to use our understanding of conceptual change to improve science education. The educational implications of research on conceptual change make clear that presentation of information should not be the only goal of teaching science. Students may need guidance in their efforts to make sense of their experiences in science. Determining the nature of that guidance is the driving force for research on conceptual change. Therefore, intervention studies offer an important component in any program of research on conceptual change.

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