Theorizing Concept Learning in Physics Education Research: Progress and Prospects

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Abstract

Research on conceptual change addresses the question of how the conceptual resources that learners bring to the context of formal instruction are transformed into conceptual understanding consistent with the accepted knowledge in some domain. Research has been conducted on conceptual change in domains such as science, mathematics, history, and economics. Physics represents an important scientific domain in conceptual change research, as many of the core theoretical perspectives that have been developed have their roots in investigations of K-16 physics learning. Over the years, many reviews have synthesized this literature in a variety of different ways. In our review, we complement this large body of prior reviews by building a multi-layer landscape of current work, so as to unpack the multiple dimensions and types of knowledge involved in conceptual change. The landscape we offer is grounded in the foundational work on the nature of concepts and conceptual change, our first layer of analysis. Then, the second and the third layers address, respectively, the role of representations (such as language, visual representations and simulations, equations, and gesture) in concept representation and learning, and the interplay between the epistemological practices of explaining, modeling and arguing and conceptual change. We then review the literature on the relationship between conceptual change, metacognition and student's epistemologies, the fourth layer of analysis. Lastly, we turn to a fifth layer that expands the scope even further to examine how learner identity interacts with concept learning in disciplinary domains.

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Introduction

In the late 1970s there was a growing sense among university physics instructors that supporting effective learning of physics is not only a matter of optimizing the delivery of clear lectures and designing supportive demonstrations. Eric Mazur described the apparent success of students in university courses as “a complete illusion, a house of cards” (Lambert, 2012). A “simple” test, the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992) composed of qualitative questions on the concept of force that were formulated in everyday language was administered to thousands of undergraduates in the southwestern United States. It showed that after a semester of physics, students still used similar naïve patterns of thinking to those they had used at the beginning of the term. Mazur went on to observe that while students ostensibly exhibited proficiency with handling equations and formulae, they did not seem to understand their real meanings and reverted to Aristotelian logic. An example Mazur gave is that students could recite Newton’s Third Law and use it in numerical applications, but when asked to think about a specific real-world context like the collision between a heavy truck and a light car, many students were convinced that the heavy truck would exert a larger force. Tellingly, when Mazur gave the Force Concept Inventory to his students, he recounted that a student asked him: “How should I answer these questions—according to what you taught me, or how I usually think about these things?”

Observations of this kind help introduce the main problem that research on conceptual change has been addressing since the 1970s: learning of physics in formal settings cannot discount the qualitative intuitions that individuals form through years of experience in the world. Like the studies on the Force Concept Inventory, many others strikingly demonstrated students’ awareness of the difference between what they learn in school and what they know from their experience (for a comprehensive bibliography see Duit, 2009). An influential video, *A Private Universe* (Schnepps & Sadler, 1989), captured the responses of Harvard graduates when asked to explain the seasons. Similar to the explanations given by younger students prior to instruction, most of them erroneously said that the Earth is closer to the Sun in summer and further away in winter drawing on their intuitions that distance from a heat source influences its effects. When asked to mobilize their knowledge, their experiential knowledge was more convincing and was activated even if the students had “learned” the scientifically normative explanation. The discovery of this discrepancy between “what is learned at school” and “what I think” is at the basis of much research that aims to unpack both the naïve, non-expert knowledge developed by experience and how it both conflicts with and supports the development of more normative understandings.

Over the past five decades, research on conceptual change has matured and the scope of interest has expanded. Typical questions that orient contemporary research programs in this area include:

- *How should we characterize both the nature of intuitive knowledge prior to instruction and expert scientific conceptual knowledge? What transformations are needed for successful learning of scientific concepts? i.e. How does conceptual change occur?*

- *How is conceptual knowledge represented and how are different forms of representation (including iconic/analogical representations, such as mental models, visual diagrams, and gestures and propositional representations, such as language and mathematics)* *involved in the process of conceptual change?*

- *Central to scientific knowledge construction are epistemic practices like generating explanations, modeling and argumentation. Are these important for conceptual change? How are these practices related to conceptual change?*

- *How important is a learner's metacognitive awareness of their own learning about scientific knowledge to conceptual change? What is the relevance of the learner's implicit views of knowledge and knowing?*

- *What is the role of the learner's sense of who they are - their identity - in conceptual change? And conversely, how does conceptual change contribute to the development of a learner's identity?*

In this chapter, we review important lines of research that have addressed these questions and we highlight the main publications that the reader can consult to gain a deeper understanding of the research findings reported and issues discussed.

Our Approach to this Chapter

Theories of concept learning and conceptual change are foundational for Physics Education Research, with many of the core theoretical perspectives in the field having their roots in learning of K-16 physics topics (e.g., Brown & Hammer, 2008; Nersessian, 2008; Posner, Strike, Hewson & Gertzog, 1982; diSessa, 1993; diSessa & Sherin, 1998; Duit, Goldberg & Niedderer, 1992; Hammer, 1996; Levrini & diSessa, 2008; Minstrell, 1992; Viennot, 2001). The aim of this chapter is to characterize the progress that has been made as well as enduring challenges in this field, including our perspective on how to navigate the diversity of theoretical foci and methodological approaches. This review of the literature on theories of concept learning in PER is based on the ideal of convergence and complementarity of research perspectives adopted in the recent volume on conceptual change edited byAmin and Levrini (Amin & Levrini, 2018). As in the aforementioned volume, we believe that the field of conceptual change is at a juncture. Over the past several decades, the field has generated multiple theoretical perspectives, maintaining a stance of theoretical pluralism (See, for example, the range of contributions to the following edited volumes: Koponen, 2014, Limon & Mason, 2002; Schnotz, Vosniadou & Carretero, 1999; Sinatra & Pintrich, 2003; Vosniadou, 2013). While helpful for making sense of phenomena as complex and multi-faceted as conceptual change, theoretical and methodological diversity can also impede a general goal of cumulative knowledge construction.

A number of chapters in previous handbooks and edited volumes on science education and conceptual change have surveyed the state of research in conceptual change (Amin & Levrini, 2018; Amin, Smith & Wiser, 2014; Brown & Hammer, 2008; diSessa, 2022; Rusanen & Pöyhönen, 2013; Sherin, 2018; Vosniadou, 2013). Many have noted a trajectory of increasing attention to the roles of multiple types of knowledge elements and their interactions in concept representation and change. For example, Amin, Smith & Wiser (2014) outlined three historical phases of research in the field as follows: in Phase 1, the field aimed at uncovering the domain-specific nature and content of student conceptions in particular domains (rejecting a domain general view of concept development); Phase 2 (spanning the 1990s and 2000s) moved from content accounts to process accounts and also broadly acknowledged that many kinds of knowledge elements are necessary for understanding conceptual change processes; in Phase 3 (underway in 2014) research began to examine the interaction of multiple and diverse knowledge elements of different formats and at different levels (understood as knowledge systems) and accordingly expanded how instructional design was approached.

As opposed to a historical overview, in this chapter, we focus on the landscape of current work: the layers and linkages involved in working towards a theoretical understanding of how knowledge systems interact at multiple levels (see Fig.1). The first layer we examine is foundational; we describe how researchers have characterized the nature of concepts and conceptual change. In this first layer, researchers try to understand the *functional core of knowledge systems* and their transformations. They use the notion of a concept (or some related construct) to characterize how learners and scientists establish some order in their understanding of the world and they provide characterizations of concepts that are formed and transformed. In the second layer researchers try to understand more explicitly *how* conceptual knowledge is represented more explicitly: considering different representational systems (e.g., linguistic, mathematical, gestural), contrasting different forms of representation (e.g., analogical and propositional) and locating representations as either internal (mental) or external (public). By making these distinctions and characterizing different knowledge types in these terms, it is then possible to examine how these representations are involved in processes of conceptual change. The third layer expands the scope of analysis to address what learners and scientists do with their knowledge. That is, attention in this layer shifts to the epistemic *practices* at the heart of scientific knowledge construction and thus researchers examine the interplay between conceptual change and the practices of constructing explanations, models, and arguments. The fourth layer goes beyond the first three by examining the relationship between concept learning and learners' metacognitive and epistemological ideas and implicit orientations to the nature of knowledge, understanding, and learning. The first four layers, while necessary for a full understanding of conceptual change, leave in the background the actual person whose knowledge is changing. Thus, in the last layer, researchers consider conceptual change in a larger context, adding attention to the "flesh and blood" of learners' goals, their sense of themselves and their emotions to the "skeleton" of the representations and cognitive processes attended to in other layers. Centrally, in this layer, we examine research that focuses on how learner identity interacts with concept learning in disciplinary domains.

We have chosen to use the heuristic notion of a "layer" to characterize analytically distinct perspectives on the integrated knowledge systems and their transformations that we seek to understand. The "layer metaphor" is intended to provide an increasingly more comprehensive picture, progressively enlarging its scope and acknowledging the greater complexity of the phenomenon of conceptual change. We might have considered using the notion of "dimension" rather than "layer." Indeed, we do consider more dimensions as we add layers of analysis and it is true to say that to study conceptual change is to study a multi-dimensional space. Alternatively, we might also have considered using the notion of a "frame of reference" as an organizing idea. As we shift between layers we sometimes bring different conceptual frameworks which function like reference points that bring different phenomena into view. We might also have used the notion of "level" because there is a sense in which as we move from a layer to the next, later levels subsume earlier levels. All three metaphors would have been effective in showing that conceptual change as an object of study can be analyzed from multiple perspectives, revealing different aspects of the phenomenon, depending on the purpose of the analysis. We settled on the notion of a "layer" because the above metaphors do not apply uniformly well as we move throughout our five layer scheme. As we move from one layer to the next, at times it is appropriate to say that a new dimension has been added to the analysis, at times there is a shift in frame of reference and at times we seem to have moved up a level of analysis, but none of these descriptions apply across the board. Researchers' different orientations to understanding conceptual change cannot be so neatly characterized. Lastly, we should clarify that the layers are not presented as "historical phases" that research on conceptual change has moved through, as outlined in Amin, Smith and Wiser (2014), but instead are considered to be an *a posteriori* conceptual reconstruction inspired by the synthetic analysis reported in Amin and Levrini's (2018) edited book.

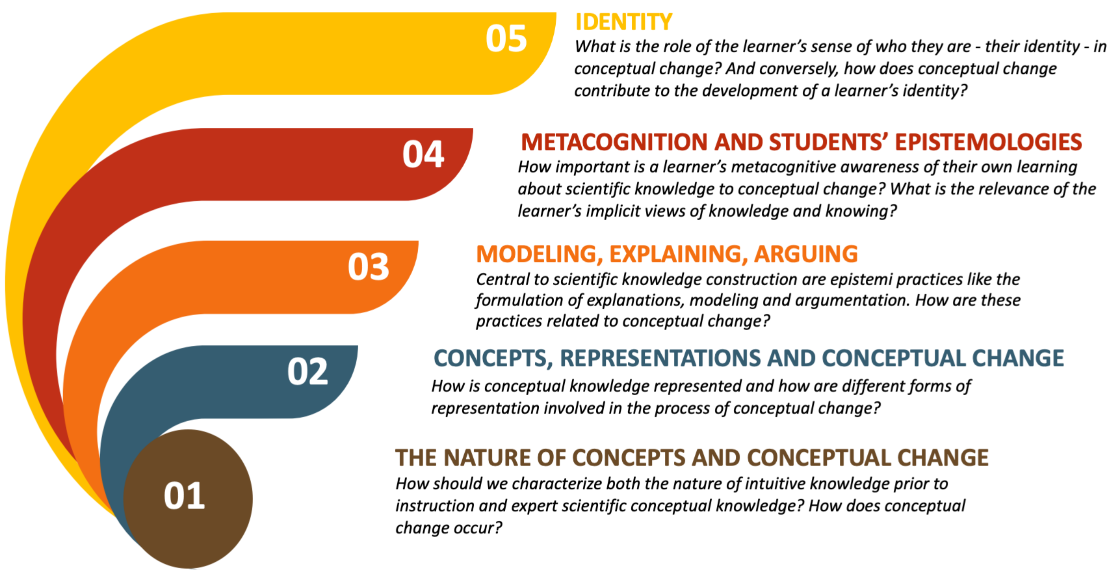

Figure 1 – Review overview: layers

While the notion of layers suggests independent foci, we emphasize that none can be really understood without attention to others, the notion helps reduce complexity for the purpose of analysis offering a heuristic clarity as researchers tackle specific aspects of a larger problem. We give a fairly general account of conceptual change research in science, broadly conceived, but when possible, clarifying examples to illustrate theoretical constructs or theoretical debates are taken from the specific domain of physics.

Layer 1: Characterizing the nature of concepts and conceptual change

Researchers have explored the nature of concepts and conceptual change from a variety of different research traditions. We begin our review of these traditions by making a broad distinction between what we call a “practice-oriented” physics education tradition and a number of traditions that can be said collectively to engage in cognitive modeling of concepts and conceptual change and have, as we explain below, converged to a considerable degree despite some important differences.

We view the practice-oriented tradition as emerging from the early recognition mentioned above concerning a distinction between students’ qualitative understanding of physical phenomena and skills in quantitative problem solving resulting in an interest in “concepts” and “conceptual understanding” (see Driver & Easley, 1978; Scott, Asoko & Driver, 1992 for early reviews).We refer to this tradition as “practice-oriented” because typically concepts are characterized as they might be characterized in textbooks or high-level objectives in curricular documents. The focus is on the impact on teaching and instruction, much more than on the theoretical research aiming to construct cognitive models of students’ conceptualizations or investigating how students’ knowledge differs from targeted canonical conceptions or characterizing how learning takes place. In this tradition, learners’ concepts have often been characterized as “misconceptions” – qualitative understanding of physical phenomena that often emerge from experience that lead to predictions and explanations that are at odds with canonical scientific concepts.

Many teaching resources have been produced within this tradition. Surveys on different concepts (e.g., energy, momentum, motion, graphs in kinematics) have been designed and tested, following the model of the Force Concept Inventory (e.g., Beichner, 1994; Ding, 2007; Neumann, Viering, Boone & Fischer, 2012; Singh and Rosengrant, 2003). Tutorials (e.g., McDermott, Shaffer et al, 2012) and curricula (e.g., Crouch & Mazur, 2001; Robinson, Otero & Goldberg, 2010; Sokoloff & Thornton, 1997) have been designed to support students in moving from intuitive to more canonical scientific understandings. Furthermore, curricular reform documents (Millar & Osborne, 1998; NGSS Lead States, 2013) have made the case that science curricula need to be organized around “core concepts” or “explanatory frameworks” as a strategy to reduce the size of curricula judged to be overloaded with too much factual content and lacking in conceptual coherence.

In contrast, there is a broad class of traditions of research on concepts and conceptual change that is engaged in cognitive modeling. We use the phrase “cognitive modeling” broadly here to refer to any attempts to deconstruct learners’ and scientists’ conceptual knowledge and concept learning in terms of knowledge structures, processes of activation of these structures and mechanisms that account for how knowledge structures are reorganized. Such attempts can be seen broadly as motivated by a constructivist understanding of teaching and learning whereby it is understood that learning something new must always be built on what the learner already understands, even when it is acknowledged that transformations and reorganizations in learners’ initial knowledge structures will be needed. While we acknowledge differences between a range of theoretical traditions, and will review these differences in this section, we begin by characterizing what we believe most researchers engaging in some form of cognitive modeling agree on about the nature of concepts and conceptual change (a view that can be distilled from surveys of edited volumes of conceptual change research; see Amin & Levrini, 2018; Vosniadou, 2013).

As work on conceptual change matured and theoretical perspectives were refined it has become increasingly clear that concepts cannot be understood as unitary entities as the popular, but loose, metaphor of concepts as "building blocks of thought" suggests (Amin et al., 2014). There is now wide agreement that physics learners (and indeed, science learners more generally) bring to formal instruction an intuitive informal way of conceptualizing specific aspects (or domains) of the world (e.g., force and motion; thermal phenomena; matter) that differs in many ways from the way that a physicist conceptualizes these domains. A physicist's knowledge is more coherently organized, integrates qualitative and quantitative understanding, and is often organized around idealized explicit models. In contrast, learners' conceptualization of the world is often implicit, characterized in terms of intuitive, qualitative knowledge that emerges early in life through interaction with the world, and is limited in its coherence and scope of application. Moreover, researchers widely agree that we need to characterize learners' and scientists' understanding in terms of knowledge systems composed of many elements that collectively allow learners and scientists alike to make sense of the physical world, offer explanations of what they observe and make predictions about the outcomes of events. As we will address in more detail in the next section on layer two, these knowledge elements are diverse, including intuitive schemas emerging from interaction with the world, concepts, mental models, linguistically formulated beliefs, mathematical representations, diagrams and even gestures. While some knowledge elements are novel acquisitions as a result of formal instruction, crucially many knowledge elements in learners' and scientists' knowledge systems are the same. Key to the process of concept learning are processes of integration of multiple knowledge elements and reorganization. It is also widely agreed that engaging learners in the epistemic practices of constructing explanations, modeling and argumentation drive these processes (see discussion of layer three). Moreover, this is accompanied (and indeed supported) by a greater (metacognitive) awareness of one's own knowledge and understanding, including an awareness of the epistemic role of this knowledge (which we discuss in the section on layer four).

Sherin (2018, p. 74, emphasis added) captures the core of this emerging consensus view in terms of the following, generically formulated, assumptions:

- There is a *system of elements*, described at *multiple levels*.
- This system exhibits at least some *variability* in behavior depending on *context*
- Changes to the system are often driven by some sort of *external influence*
- *Change can be slow and incremental*
- The changes might result in the construction of **"***hybrids***"**

Within this emerging consensus, researchers working within a variety of different disciplinary traditions and perspectives have highlighted different aspects of concepts and conceptual change and have sometimes disagreed about specific issues within this broader consensus. Sometimes differences in perspective are not explicitly acknowledged, resulting in difficulties in communication among researchers adopting different perspectives. Sherin (2018) discusses what he calls "ontological slippage" across perspectives, including slippage between those adopting practice-oriented and cognitive modeling perspectives. What he means by this is that researchers will often engage in discussions and debates on concepts and conceptual change in science learning slipping, without explicit recognition, between different ontological assumptions about the nature of concepts. Having discussed the current consensus view, we now turn to discussing distinguishing features between theoretical perspectives on the nature of concepts and conceptual change.

In science education, a prominent theory of conceptual change is the theory of conceptual accommodation developed in the early 1980s by Posner, Strike and colleagues (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1985). This theory, which has been very influential among science education researchers, was grounded in broad epistemological considerations of knowledge change inspired by Piaget's (1954) account of assimilation and accommodation in child development and Kuhn's (1962) account of theory change in the history of science. Posner and Strike and colleagues built on a common idea found in Piaget and Kuhn that conceptual understanding is framed within larger knowledge structures and, therefore, changes in understanding implicate elements of these larger knowledge structures, including other concepts, beliefs and epistemological assumptions. Posner and Strike translated this view into an account of the conditions for conceptual change in science learning. They suggested that a new conception would be learned to the extent that there was 1) dissatisfaction with an existing intuitive (noncanonical) conception; 2) the new scientific conception was made intelligible - e.g., through analogies and metaphors; 3) the new conception is seen as plausible in being consistent with observations, other conceptions and beliefs; and 4) the new idea seems fruitful in opening up possibilities for further understanding. These conditions can be glossed as a rational account of how a shift in the relative "status" of an existing naïve conception and the scientific conception to be learned can be achieved. This view inspired many investigations into science learning and the design of effective instruction (e.g., Beeth, 1998; Hewson & Hennessey, 1992). This perspective has been criticized for being an overly rational account of conceptual change.he original model was indeed later revised by Strike and Posner (1992) to incorporate greater attention to less explicit processes of learning and less "cognitive" factors such as learners' goals and motivation, a development that we treat within our discussion of layer four.

Another tradition of science education research on concepts and conceptual change, the Knowledge Integration perspective (Clark & Linn, 2013; Linn & Eylon, 2011; Linn et al., 2018), has adopted a relatively generic approach to the cognitive modeling challenge. From this perspective a broad distinction is made between intuitive and canonical knowledge elements. Concept learning is characterized in terms of the learner adding, distinguishing, reflecting on and integrating ideas. Through a protracted process of guided learning the learner gradually incorporates more canonical knowledge elements into their knowledge system and reorganizes this knowledge such that canonical explanations and predictions can be made in the context of formal scientific reasoning. This perspective has been applied to learning and instruction in many science domains, including important concepts in physics: force and motion (e.g., Clark et al., 2011) and heat and temperature (Clark, 2006).

A third account of conceptual change in science learning emerged from research on conceptual development in the field of developmental psychology. This theoretical tradition can be traced back to the early to mid-1980s as developmental psychologists were becoming dissatisfied with Piaget's stage view of cognitive development (Carey, 1985). Developmental psychologists rejected the view that conceptual development was governed by stage-like changes in the capacity to represent information about the world and engage in reasoning that applied generally across whatever the developing child was thinking about. Instead, a domain-specific view of conceptual development was articulated that characterized conceptual growth in distinct domains independently. Some domains were privileged in that infants seemed to begin life already endowed innately with some skeletal conceptual knowledge about inanimate objects, goal directed agents, number and space that guided their learning in these domains (see Carey, 2009 for a comprehensive account of conceptual development that builds on the innate core cognition of infants). The central idea was that children's conceptual development occurs within domains that are guided by skeletal explanatory conceptual structures that categorize distinct types of entities in the world and support explanations and predictions about their behavior. That is, core concepts in each domain are embedded within theory-like structures that are used to make sense of experiences in the world and the verbal input of others, gradually getting enriched and transformed in the process. This account of conceptual development was inspired by Kuhn's (1962) account of theory change in the history of science. The enrichment of skeletal conceptual structures with experience was seen as analogous to knowledge growth within paradigms in periods of so-called "normal science." More fundamental changes involve restructuring of core concepts and the construction of novel explanatory theoretical frameworks were seen as analogous to the construction and adoption of a new "paradigm." It is the latter that has been referred to as "conceptual change" in the particularly narrow sense of changes in a knowledge structure requiring fundamental changes in the core concepts of a theoretical structure.

The developmental psychologists Susan Carey, Carol Smith and Marianne Wiser began to apply this perspective on conceptual development to learning scientific concepts, focusing on the developing understanding of matter (with core concepts of weight and density) (see Smith, Carey and Wiser, 1985) and thermal physics,with core concepts of heat and temperature (Wiser, 1987). They argued that learners came to the contexts of formal science instruction in each domain with core concepts that were quite different from the concepts that were the core of the scientific theories they were being taught. Specifically, they argued that initially undifferentiated concepts (weight/density and heat/temperature, respectively) needed to be differentiated. Following Kuhn (1962, 1977), they used the concept of "incommensurability" to characterize the learning challenge – i.e. learners brought conceptual structures that related concepts in a way that was incommensurable with (not translatable to) the concepts in the target conceptual structure. Learning did not simply involve forming new beliefs that related existing concepts in different ways; it involved changes to the concepts themselves. While still embracing the conceptual-change-as-theory-change idea, this perspective has evolved in various ways. Motivated in part by more detailed cognitive-historical accounts of conceptual change in the history of science (Nersessian, 1989, 1992, 2008), more recent accounts have addressed specific aspects of the conceptual change process from a theory change perspective: a more incremental picture of the transformations of pre-instruction conceptual structures into more canonical structures in the context of theory-based instructional interventions (Smith, 2007; Smith & Unger, 1997; Vosniadou, 2013; Vosniadou & Brewer, 1992; Wiser & Amin, 2001, 2002); a more detailed picture of concepts as mental representations that are characterized in terms of *reference* (what entities and situations in the world they pick out) and *inferential role* (what networks of beliefs they participate in to support reasoning) and conceptual structures consisting of multiple knowledge elements such as perceptual schemas, concepts, mental models, linguistic and mathematical propositions, and epistemological beliefs (Carey, 2009; Wiser & Smith, 2016); and more explicit accounts of the mechanisms of change highlighting the role of propositional representations (linguistic and mathematical) as placeholders for targeted conceptual structure in interaction with modeling (a mechanism referred to as Quinian bootstrapping) (Carey, 2009; Wiser & Smith, 2016).

An aspect of conceptual-change-as-theory-change that has been scrutinized in particular cases is "ontological" recategorization (Chi, 1992, 2013; Vosniadou & Brewer, 1992; Wiser & Amin, 2001). In such cases, the learner initially classifies a concept within a broad category very different from the category a scientist would classify the concept. While initially seen as an aspect of the theory change view, a distinct theoretical tradition emerged within cognitive science that focused narrowly on ontological change taking place during the acquisition of expertise (e.g., Chi, 1992, 2005, 2013; Henderson, Langbeheim & Chi, 2018; Slotta, Chi & Joram 1995). Concepts were seen as represented within hierarchical ontological structures and learning was seen as involving an "ontological shift." The claim is that many scientific (often physics) concepts (e.g., heat, light, electric current) are originally misclassified by learners within a broad material substance ontology. Learning requires the construction of an entirely new ontological category - the interaction-based or emergent process - and recategorizing these misclassified concepts to the newly constructed ontology. Some instructional interventions have been designed assuming this view of concept learning and have demonstrated some success in improving students' understanding in challenging domains (Chi, 2013).Theory change and ontological shift accounts of conceptual change have something important in common: they characterize the conceptual understanding of the learner, even before instruction, as constrained in some way (either by a theory or ontological category). Moreover, the assumption is that these constraints operate whenever the learner makes use of that concept, resulting in a certain degree of consistency in learners' reasoning across situations where the concept is relevant.

In contrast to the theory change and ontological shift perspectives, the Knowledge-in-Pieces perspective on conceptual change in the learning sciences has posited greater fragmentation in their models of learners' pre-instructional understanding (diSessa, 1983, 1988, 1993, 2018a). While the Knowledge-in-Pieces perspective is grounded on the assumption of cognitive complexity, the process of everyday sense-making about the physical world is viewed as patterned and can be investigated. In particular, clinical interviews or classroom data reveal that such a sense-making process draws on many intuitive resources, referred to as phenomenological primitives (p-prims) that are activated in combination in any given situation often revealing considerable inconsistency in reasoning across situations (diSessa, 1993). Science concept learning from this perspective involves the reorganization of many elements in a rich knowledge system populated by many knowledge elements. Rather than undergo "restructuring" as theory change theorists would posit, students must learn to refine the conditions of activation of their knowledge elements in ways that enable them to formulate explanations and make predictions about physical situations as a scientist would. Thus, there is considerable continuity between learner and expert at the level of the knowledge elements they possess and activate; what changes are conditions of activation. This theory was developed and illustrated primarily in the domain of mechanics.

P-prim theory was built on and developed in a number of directions often in the context of applications to topics in physics (see diSessa, Sherin and Levin, 2016 for an overview of this development). One important direction was the development of a systems account of a type of scientific concept referred to as a coordination class (diSessa & Sherin, 1998). Scientific concepts like *force*, *time*, and *acceleration* can be understood as "coordination classes" in the following sense: a knowledge system composed of many elements is activated in a way sensitive to context such that the scientist can "see" *force*, for example, in the appropriate situations and can draw inferences consistently across situations that might vary considerably at surface level. Coordination class theory has been applied to a number of topics in physics and mathematics (Barth-Cohen & Wittman, 2017; diSessa & Sherin, 1998; diSessa and Wagner, 2005; Wittman, 2002). It also has implications for teaching and instruction design. It has proved to be very useful for unpacking and understanding the effectiveness of teaching choices - e.g., to explain why using multiple contexts and multiple definitions for the same concept can be a fruitful move to foster processes of conceptual change (Levrini & diSessa, 2008). Furthermore it influenced the design of a thermodynamics module that was revealed to be effective in fostering appropriation (Levrini, Levin & Fantini, 2020). This account of concepts and concept learning from the perspective of systems required close attention to the interaction of different types of knowledge elements represented in different ways, something we elaborate on in the next section.

As we have seen in this section, a number of different theoretical traditions have characterized concepts and conceptual change in different ways. Along the way, our account has appealed to various types of knowledge elements – concept, theory, p-prim, equations, language – but little was said about how these differ, in what sense they constitute different forms of representation and ways of reasoning about physical systems. In the next section, we look at how researchers have examined concepts and conceptual change through our next layer of analysis. While we point out how different theoretical traditions have been particularly interested in different representational forms and their interactions, our focus will be on the distinct forms of representations themselves and their functions and affordances and their roles helping learners come to understand and reason about the world as a scientist would.

Layer 2: Representation, concepts and conceptual change

Scientific concepts like *atom*, *energy*, *force* and *heat* are tools that scientists have invented to parse the physical world into different kinds of entities, relations and processes; these scientific concepts are embedded in theoretical propositions and models that support explanation and prediction. Theoretical propositions – general statements about how the physical world behaves and relations between variables are formulated in language (e.g., "When two objects are placed into contact, heat flows from the object at higher temperature to the object at lower temperature") and mathematics (e.g., $F = ma$). Models are often represented using diagrams (e.g., energy level diagrams; a diagram of an idealized object hanging from a spring representing an idealized simple harmonic oscillator). Opening any science textbook immediately reveals the technical use of linguistic, mathematical and diagrammatic representations to convey scientific ideas. The highly mathematical nature of the field of physics means that a wide variety of mathematical notational systems are used in this domain in particular.

We now review research on conceptual change that adopts a second layer of analysis attending explicitly to the representational tools used to represent scientific knowledge and engage in knowledge building by scientists and learners (see Amin, 2018 for discussion). Two broad distinctions between types of representations are important when considering this layer of analysis: the first is the contrast between analogical/iconic and propositional representations; the second is the contrast between internal/mental and external/public representations. These distinctions are important because they help clarify differences between theoretical traditions examining the role of representations in conceptual change as well as the distinct roles that particular representations play in specific aspects of the conceptual change processes.

Analogical/iconic representations are those that stand in for what they represent by virtue of similarity (e.g., a picture or diagram of a dog, however schematic, resembles actual dogs); they are inferentially very rich. For example, if you have recently consulted a map capturing the locations of various cities and towns, you can easily infer relative distances that you haven't actually thought about before by recollecting the map and simply "reading off" the relative distances you are interested in. It is in this sense that pictures are said to be "worth a thousand words" (Larkin & Simon, 1987). We judge an analogical representation by its degree of resemblance to what it represents and how useful it is for a particular purpose. Analogical/iconic representations are propositionally indeterminate, however. It is not always clear what a picture or diagram is trying to communicate. A picture of a cat on a mat might be trying to communicate the spatial relationship captured by the statement "The cat is on the mat" but it might also be a comment on cats tending to enjoy sleeping on mats, an appreciation of the peacefulness of the scene, etc. Propositional representations – such as statements in natural language or mathematical equations – capture precise relationships between the entities symbolized and can be judged to be true or false.

We can also contrast representations in terms of whether they are external/public representations or internal/mental representations. Natural language, mathematical equations, diagrams, gestures are all external representations that can be directly observed and are, thereby, public. These manifest themselves in oral communication or in print. There are also internal/mental representations that are appealed to by cognitive and learning scientists to account for knowledge representation and learning in individuals; these are constructs that refer to unobservable entities that help researchers make sense of explanations, predictions and problem solutions manifested in external public representations produced by learners and scientists. Both internal and external representations can be analogical/iconic or propositional.

One tradition of research has adopted a discursive or social semiotic perspective on science learning and some of this work has focused on learners' development of conceptual understanding (Fauville, Andersson-Lantz, Mäkitalo, Dupont, & Säljö, 2016; Lemke, 1990, 1998; Schoultz, Säljö, & Wyndhamn, 2001). This tradition has largely restricted its focus to examining how scientific theories and models are manifest in semiotic systems (language, mathematics, diagrams, gesture) and how learning involves the appropriation of the use of elements of these semiotic systems, often through interaction with others. While some researchers working within this perspective have been open to considering how internal mental representations interact with semiotic systems in learning (Schoultz et al., 2001) others have explicitly rejected the appeal to internal mental constructs (Lemke, 1990, 1998). Either way, proponents of this perspective have emphasized detailed descriptions of how scientific knowledge is realized in semiotic systems and have conducted detailed analyses of the moment-to-moment use of semiotic tools (often more than one simultaneously) in the context of interaction in learning contexts. That is, emphasis has been on documenting the semiotic dynamics of learning events with less emphasis given to the knowledge states of individuals. It is not surprising then that researchers in this tradition will not typically use the phrase "conceptual change" to refer to the phenomena they study, a phrase which implies that focus is on conceptual knowledge represented mentally and that change in conceptual knowledge states within individuals is being captured.

That said, most researchers with an interest in representation as a layer of analysis when examining conceptual change appeal to both internal and external representations. We will review how representations of different kinds have been involved in these accounts of conceptual change, pointing out how different research traditions have emphasized particular learning mechanisms with somewhat different implications for instruction.

Research on conceptual change within the cognitive developmental psychology tradition with its emphasis on concepts embedded in theory-like structures took a particular interest in mental models as analogical mental representations that represent spatial and causal relationships between entities in a physical system (Gentner & Stevens, 1983; Johnson-Laird, 1983). Mental models figure in this research in two ways. First, learners' non-canonical understanding is sometimes characterized in terms of mental models - e.g., see Smith's account of early models of matter (Smith, Snir & Grosslight, 1992), Vosniadou's description of children's models of the earth (Vosniadou & Brewer, 1992) and Wiser's Source-Recipient model of heat/temperature exchange (Wiser, 1995). Mental models also serve as instructional targets that can guide the process of conceptual restructuring. That is, if learners can construct a schematic mental model of matter composed of particle-like entities packed to some degree in a unit space, this can drive a differentiation of the concept of weight and density. An instructional tool that can be used to achieve this is external imagistic representations e.g., dots-in-box diagrams used by Smith (Smith, 2007; Smith & Unger, 1997) that embody the kind of conceptual relationships being targeted. For example, in this case the claim would be that learning to use the dots-in-box model to represent material substances guides the mapping between dots and microscopic particles making up a substance and between the box and unit volume. It is suggested that this helps learners differentiate weight/mass and density as extensive and intensive quantities, respectively. Analogical reasoning was seen as a key learning mechanism to drive conceptual restructuring (see also Wiser & Amin, 2001, 2002 for an account of teaching using visual analog models to differentiate heat and temperature).

Consistent with the interest in the 1970s and 80s in emphasizing qualitative understanding of concepts, work on conceptual change from this theory change perspective emphasized the role of mental models, diagrammatic representations and analogical reasoning. While the importance of understanding and using propositional representations was always acknowledged, researchers wanted to counteract the over emphasis in traditional instruction on learning concept definitions and quantitative problems-solving. More recent work in this tradition has begun to recognize an important role for propositional representations in the conceptual change process itself. As mentioned briefly in the last section, Carey (2009) has developed an account of conceptual change in which propositional representations (both linguistic and mathematical) can play a role in bootstrapping conceptual restructuring. That is, learners will encounter theoretical propositions in some domain (e.g., $D = M/V$; "Specific heat is the quantity of heat needed to raise the temperature of one gram of a substance by one degree Celsius.") sometimes before they have developed an understanding of key concepts expressed in those propositions. The propositions express relationships between the targeted concepts and so serve as a placeholder that can constrain and guide the conceptual change process. In Carey's account, analogical reasoning and mental model construction can provide the resources for developing meaningful understanding but this will be constrained (supported) by initially shallowly understood propositions. This account of conceptual change has been inspired, in part, by Nersessian's (1992, 2008) account of conceptual change through constraint-based modeling in the history of science based primarily on her cognitive-historical analysis of the conceptual innovations of Faraday and Maxwell in understanding electromagnetism. The account viewed conceptual restructuring as driven by the interaction between analogical and propositional representation, both external and internal. This account of conceptual change does not have direct implications for how one should sequence instructional activities. While some might interpret this account as suggesting a return to a leading-with-concept-definitions approach to instruction, leading with model building is consistent with this epistemic account of the conceptual change process (see Smith & Amin, forthcoming for a discussion of this point).

Research on conceptual change in the tradition of the learning sciences adopting the Knowledge-in-Pieces (or broadly, resources) perspective has also taken an interest in the specifics of representations of different kinds (diSessa, 1993; diSessa, Sherin & Levin, 2016). First, it is important to mention that a p-prim (mentioned in the last section), a primary sense-making resource, is understood to be "sub-conceptual;" that is, a p-prim (of which there are many) is a smaller knowledge structure than a concept, itself understood as a coordination class, a knowledge system composed of many elements of different types. The initial emphasis on p-prims was intended to draw attention to schemata that emerged from bodily interactions with the world; this tacit, bodily-based knowledge provides a phenomenological (experience-based) and basis for understanding the physical world, providing a basis for explanation but itself requiring no explanation. Learning involves the gradual shaping of activation priorities of p-prims. Explaining how this occurs we must appeal to other representational tools.

First, some researchers have argued that intuitive structures like p-prims can be activated strategically by inviting learners to think about situations where that intuitive structure is likely to have high probability of activation and suggesting that this is analogous to some target situation (Brown & Clement, 1989; White, 1993). So-called "anchoring intuitions" (e.g., the intuition that a spring pushes back with force on a book placed upon it) can be projected analogically to target situations in which learners would not activate a useful intuition (e.g., a table is not intuitively seen as pushing back with force on a book place upon it). Brown and Clement (1989) have argued that for these analogically driven activations to be successful, a "bridge" is needed, a situation with features resembling both the anchor and target situations (e.g., a book on springy plank of wood.) What these "bridging analogies" do is help learners construct mental models of target situations that incorporate strategically useful intuitive structures (e.g., constructing an explanatory mental model of the surface of a table as composed of springy particles pushing back up on things placed on it enables learners to see the table as exerting an upward normal force). White's (1993) ThinkerTools computer-based learning environment for mechanics incorporates similar design features: the movement of a dot in a computer simulation governed by Newtonian principles is represented in a highly schematic but analogical fashion; the dot can be manipulated using a joystick which can impart an "impulse" which changes the velocity by one unit. In this environment, visual models of intermediate abstraction embody Newtonian principles and are interpreted using intuitive knowledge structures to help learners construct productive mental models that support scientific reasoning about force and motion. Of course, selecting situations that can serve as anchoring intuitions and designing visual representations and computer based simulation environments can be seen from the perspective of the teacher/designer to serve as a basis for analogical reasoning that can guide learning a target concept. But from a Knowledge-in-Pieces perspective, variability is to be expected in what knowledge elements are activated by different learners in different situations (Kapon & diSessa, 2012).

Linguistic and mathematical propositions also guide the activation of intuitions. Early on in his development of p-prim theory, diSessa (1993) mentioned that linguistic and mathematical propositions can be sites for the activation of collections of p-prims, what he referred to as the "distributed encoding" of these propositions and he acknowledged a rich role for a wide range of knowledge resources of different representation forms including p-prims, mental models, beliefs and narratives (diSessa, 1996). This idea has been elaborated since, showing how use and understanding of propositional representations in science can be understood from a KiP perspective. Sherin (2001) has identified what he calls symbolic forms – knowledge elements each composed of a symbol template and a conceptual schema – that allow for the meaningful interpretation of physics equations and understanding how these relate to physical situations. Moreover, researchers have explored how the use of equations in the context of problem solving (Sherin, 2006; 2018) and knowledge of linguistically formulated definitions of key concepts can play the role of guiding the reorganization and selective application of knowledge elements of p-prims like a scientist would (Levrini & diSessa, 2008). Finally, Brown (2018), has argued for the importance of seeing the construction of canonical scientific explanations as involving the integration of multiple knowledge elements at different levels of organization and formats including core intuitions (similar to p-prims), mental imagery, implicit mental models, explicit models, and verbal/mathematical resources.

In another multifaceted line of work that has explicitly addressed issues of representation in science concept learning, researchers have applied ideas from second generation cognitive science - i.e. embodied cognition (Wilson, 2002). Three related ideas have been particularly inspiring: that abstract understanding is grounded in perceptual simulation (Barsalou, 2008); that many abstract concepts are understood metaphorically in terms of generalizations from sensorimotor experience with mappings reflected conventionally in language (Lakoff & Johnson, 1980, 1999); and that cognitive processes should be understand as extended beyond the mind to include the body, physical and symbolic artifacts, and other people (Clark & Chalmers, 1998; Hutchins, 1995).

Lindgren and colleagues (Lindgren & Johnson-Glenberg, 2013; Lindgren, Tscholl, Wang, & Johnson, 2016) built on the idea that abstract understanding is grounded in perceptual simulation to design effective science learning environments. Their approach has been to design mixed reality environments to engage learners' bodies as they learn about science concepts. For example, learners enact the motion of a meteor orbiting a planet while interacting with a digital simulation of a planetary system (Lindgren et al., 2016). Using the Force Concept Inventory as an assessment tool, Lindgren et al. showed that this mixed reality environment was more effective in supporting the learning of scientific concepts (e.g., Newtonian force and motion) compared to using a regular desktop simulation. This supported their claim that engaging the body was an important aspect of the concept learning process, and the assumption that conceptual understanding drew on perceptual simulations (mental reenactments of prior bodily actions carried out by learners).

That abstract concepts are understood metaphorically in terms of image schemas has been the inspiration of another thread of research on science learning from an embodied cognition perspective. Cognitive linguists have argued that implicit in natural language are extensive patterns of metaphorical mappings between abstract and more concrete conceptual domains (Lakoff & Johnson, 1980, 1999). This theory of conceptual metaphor has been used to identify mappings implicit in the language of science between abstract scientific concepts and the more concrete image schemata of containment, force, movement along a path and others emerging from sensorimotor experience. Researchers have examined a number of physics concepts from this and related perspectives including energy and entropy (Amin, 2009; Amin, Jeppsson, Haglund & Strömdahl, 2012; Brookes & Etkina, 2007; Close & Scherr, 2015; Jeppsson, Haglund, Amin & Strömdahl, 2013), force (Brookes & Etkina, 2009) and heat (Brooks & Etkina, 2015). Learning science concepts from this perspective is understood as appropriating the metaphorical mappings already implicit in the language of science. The selection and design of instructional analogies, representations and simulations can then guide learners in forming the same metaphorical mappings already implicit in the conventional language of science (see contributions to Amin, Jeppsson & Haglund, 2015).

Finally, a third important idea in the literature on embodied cognition is that the cognitive processes are extended beyond the mind (Clark & Chalmers, 1998; Hutchins, 1995). Science concept learning has been studied from this perspective as well. Some researchers have seen science concepts as realized in specialized discourses and symbolic tools with learning understood as the appropriation of these discourses and tools (Säljö, 2018). Others have described how gestures are used by learners, in interaction with other representational resources, to support their participation in scientific practices (Gregorcic, Planinsic, & Etkina, 2017) and their understanding of abstract concepts (Roth & Lawless, 2002). Indeed, the analysis of gesture is emerging as a very valuable tool for researchers investigating the subtleties of teaching and learning processes in physics and other domains (Roth, 2001; Scherr, 2008). Finally, others have examined closely the interactions between learners with each other and with their teachers showing how scientific understanding and reasoning is distributed over these interactions and so learning should be viewed as transformations in these interactions not just an internal mental process in individuals (Euler, Rådahl, and Gregorcic, 2019; Pea, 1994; Roschelle, 1992).

To conclude, we have seen in this section how a variety of research traditions have taken an interest in how concept learning and representation interact. Different traditions make different commitments to the kinds of representations to examine, the distinctions between different representational formats and where the focus is on the content of the representations or the process of use of these representations in contexts of interaction.

Layer 3: Interplay between Epistemic Practices and Conceptual Change

We turn now to an exploration of a third layer - the relationship between engagement in scientific practices and conceptual change. This layer is particularly relevant for both researchers and practitioners since the focus is on practices that can be engaged in real classroom activities that support and make visible processes of conceptual change. In particular, we refer to the epistemological practices of *explaining*, *modeling* and *formulating arguments*. These practices, together with the e*pistemic artifacts* represented by explanations, arguments, and models, are described clearly in Chinn (2018) and discussed extensively in the chapter of this

Section authored by Kapon and Berland (this volume). In that chapter, Kapon and Berland analyze epistemic artifacts and practices in relation to sensemaking and reasoning. In this section, we consider the literature that specifically relates explaining, modeling and formulating arguments to conceptual change.

In our review, we follow the approach taken in this chapter so far which is to examine how different research traditions have approached a particular layer of analysis. So in this section we will examine how different research traditions approached the meaning and relevance of the epistemic practices listed above in different ways. In particular, we will stress variations in which practices are emphasized, as well as variations in the learning goal targeted when learners engage in these epistemic practices: to facilitate particular conceptual changes or to learn to participate in the practices as an end in itself.

A useful starting point for this review is the model of conceptual change via conceptual accommodation proposed by Posner, Strike, Hewson and Gerzog (already presented in the section on layer 1). We can trace the current interest in epistemic practices back to two critiques of this "classical" model. The first critique is that the classical model focused too much on science *content* knowledge and did not take into consideration that understanding science also includes knowledge of the *processes* of elaborating science content knowledge (Duit & Treagust, 2003). In the early approaches to conceptual change, theories and models were part of the investigation into students' knowledge prior to instruction, but these theories and models were characterized mainly from the perspective of "scientists' science" (Gilbert & Zylbersztajn, 1985). Scientific theories and models were treated as historical products of science, against which students' knowledge can be compared. Examples of relevant studies of this type are the investigations into students' ideas on the concept of force (e.g., Galili, 2001; Galili & Bar, 1992; Whitaker, 1984), light and vision (e.g., Galili & Hazan, 2000), heat and temperature (e.g., Besson, 2014; Tarsitani & Vicentini, 1991).

The second critique of the classical view of conceptual change concerns the rational view of learning it initially assumed. In the classical model, the understanding of *explanation* was, more or less implicitly, inherited from logical positivism - i.e. explanations were seen as derived from rational processes such as deduction and induction (Duit & Treagust, 2003). The assumption was that if learners engage in these processes they will construct canonical scientific explanations seen as the main learning outcomes of science education. In a sense, constructing new (better) explanations was seen as a rational process of belief revision. What was not appreciated was the role of imaginative and abductive processes. Amin, Smith and Wiser (2014) made a related critique when they argued that, although the classical view of conceptual change was grounded in a Kuhnian epistemological view, from their perspective, it was not Kuhnian enough: it did not give close enough attention to changes at the level of concepts embedded in at least partially incommensurable conceptual structures. Constructing new conceptual structures that are at least partially incommensurable with the conceptual structure a learner (or scientist) already possesses requires imaginative/abductive processes.

The work by the philosopher of science Nancy Nersessian represents a milestone in connecting conceptual change research and epistemic practices, built to address both the main critiques of the classical view of conceptual change just mentioned (Nersessian 1987; 1989; 2008). She combined Kuhn's historical approach to the philosophy of science with the cognitive perspective on conceptual change and elaborated a "cognitive-historical" method to study important episodes of conceptual/theoretical innovation in the history of science. This resulted in embracing a naturalistic approach to conceptual change that moved the attention of historians from conceptual structures to the epistemic practices:

> A naturalist recasting of the problem of conceptual change in science shifts the focus of the problem from the conceptual structures themselves to the nature of the practices employed by human agents in creating, communicating, and replacing scientific representations of a domain. (Nersessian, 2008, p. 5)

Following Kuhn, Nersessian shares his criticisms of positivism:

> The positivist account of conceptual change remained largely programmatic. Specifying the exact nature of the logical relations among concepts and between concepts and empirical phenomena proved a formidable, ultimately unfulfilled, challenge. (Nersessian, 2008, p. 3)

Nersessian's "cognitive-historical" method is based on the assumption that cognitive science research, if applied to the analysis of historical texts and artifacts, can be used to understand the basis of the scientific practices; and *vice versa*, this method can reflect back to cognitive science many considerations that arise in analyzing scientific problem solving. Nersessian calls this the "continuum hypothesis":

> The cognitive practices scientists have invented and developed over the course of the history of science are taken to be sophisticated outgrowths of the kinds of cognitive strategies humans employ in coping with their environments and in problem solving of a more ordinary kind. Scientists extend and refine basic cognitive strategies in explicit and critically reflective attempts to devise methods for probing and understanding nature. Studying the science end of the continuum, thus, can lead to deeper understanding of the potential of human cognitive capacities, and contribute to cognitive science research. (Nersessian, 2008, p.6)

An important implication of this method for the narrative we are developing on epistemic practices and conceptual change is that *modeling practices constitute genuine reasoning*. This claim is embraced to expand the notions of reasoning beyond the rational logic-based practices of deduction and induction. Nersessian advocates for the importance of recognizing creative inference due to "abduction" and to the potential of model-based reasoning for providing a means of specifying the nature of the ampliative reasoning in abductive inference, such as analogy.

The research on conceptual change from a theory change perspective was largely inspired by Nersessian's account of constraint-based modeling in the history of science to design instruction that could achieve conceptual restructuring. This perspective viewed analogical reasoning as a key driver of restructuring and designed visual representations that embodied conceptual relations targeted in instruction. That is, models were presented to learners and they were guided in how to use them. In sum, theory change researchers (Smith, 2007; Wiser & Amin, 2001;

Wiser & Smith, 2016) emphasized using ready-made models to achieve targeted conceptual restructuring.

Meanwhile, research in the science education tradition (growing out of what were referred to earlier as the "practice-oriented perspective") shifted toward a more explicit focus on the processes of modeling and argumentation as learning outcomes in themselves. The main drivers of this shift, in addition to the critiques of the classical conceptual change model already mentioned, were: the pressure coming from the conception of scientific literacy embodied in the TIMSS and PISA tests in the late '90s, and from the need to stay increasingly close to school needs and instruction (Duit & Treagust, 2003). The conceptions of scientific literacy reflected in PISA, especially, pushed science education researchers to focus their attention on science processes such as questioning, elaborating evidenced-based argumentation, problem solving, communicating, self-regulation of learning, decision-making and so on. Thus, the research in science education progressively moved away from conceptual change as the primary goal for instruction. Even if the research on modeling, argumentation, generating self-explanations, and problem solving was initially primarily motivated by conceptual change (e.g., Driver, Newton & Osborne, 2000; Jiménez-Aleixandre & Brocos, 2018; Jiménez-Aleixandre & Erduran, 2007), it progressively focused on scientific practices as explicit epistemic learning goals (e.g., Erduran & Jiménez-Aleixandre 2007; Gilbert, 2004; Justi & Gilbert, 2003; Koponen, 2007; Schwarz & White, 2005; Tasquier, Levrini & Dillon, 2016). As Chinn has observed:

> Learning to engage in the practices involves conceptual change in the practices themselves--that is, conceptual change in students' very understanding of modeling, explanation, and argumentation. (Chinn, 2018, p. 206)

Similarly, Lehrer and Schauble (2015), whose work originally grew out of the educational psychology research tradition on the development of scientific and mathematical thinking, came to position understanding of and skill with modeling as the primary learning outcomes of science education. In their work, modeling is used as an organizing concept for curriculum design that integrates science and mathematics learning and instruction. While aspects of their work have addressed students' conceptual changes in particular domains (Lehrer, Schauble, Strom, & Pligge, 2003), conceptual change is primarily viewed as a byproduct of participating in extended cycles of modeling.

All the approaches to conceptual change and epistemic practices described so far in this section, view epistemic practices as the specialized practices of science. While learners are understood to bring their pre-instruction forms of understanding and reasoning, the goal is to guide students in participating in the institutional practices of science and, thereby, develop more canonical understanding in scientific domains.

In contrast, the Knowledge-in-Pieces perspective to conceptual change looks at epistemic practices more radically from the perspective of the learner and their intuitive knowledge and reasoning resources. This approach is based on two completely different assumptions from those of Nersessian. Firstly, from this perspective the history of science is not a privileged source for identifying cognitive processes relevant for conceptual change because reasoning and practices in science do not necessarily cohere with the strategies that individuals can activate for their own personal understanding. Second, the main interest from this perspective is in the epistemic practices that characterize intuitive knowledge systems rather than the epistemic practices that characterize science (even if science is the domain and the ultimate goal remains to foster learning of normative science). Thus, from the Knowledge-in-Pieces perspective, the epistemic practice that is primarily investigated for the purpose of observing conceptual change is *explaining* or *sensemaking* (as opposed to the practices of scientific modeling and argumentation). The practices of explaining and sense-making prioritize the discourses of students themselves, and learning is investigated as a form of progressive, moment-by-moment, refinement of scientific discursive practices and their appropriation into individual processes of sensemaking (e.g., Levrini, Levin, Fantini, & Tasquier, 2019).

Research by John Clement and David Brown on model construction, explanation and analogical reasoning can be seen from this perspective. They have unpacked, at a quite a fine-grained level, students' processes of explaining and explanation construction building on their intuitive knowledge resources (Brown & Clement, 1989; Clement, 1988; Clement, Brown & Zietsman, 1989). While the strategy of using bridging analogies (referred to earlier) is intended to help learners construct more canonical explanations, they, crucially, are designed to build on their experience-based intuitions and draw on basic human capacities for sense-making drawing on the abilities of mental model construction and imagistic reasoning.

A particularly close look at explanation from a learner perspective can be found in a series of studies by Kapon and diSessa within the Knowledge-in-Pieces tradition (Kapon, 2017; Kapon and diSessa, 2012). In this work, they try to identify the smallest knowledge elements that students use to generate their own explanations (so called "self-generated" explanations). These elements are called "e-prims" and, like p-prims, are "self-explanatory accounts of how things are, but apart from our experience with the physical world, their source can also be education, language, and interaction with other people; they can be encoded both verbally and nonverbally, and they can have different levels of complexity." (Kapon, 2017, p.169). From this perspective, the research problem is to unpack "people's sense of what constitutes a good explanation." The research has resulted in building a three-dimensional metric that has been shown to be "central to the evaluation of explanations of phenomena in the physical world: (1) intuitive knowledge, (2) mechanism, and (3) framing" (Kapon, 2017, p.165).

In the layer of analysis we turn to next, students' perspectives become even more central and we will see how nuanced and diversified are the types of knowledge involved in personal processes of conceptual change.

Layer 4: Metacognition and epistemological beliefs in conceptual change

In tandem with the birth and establishment of conceptual change as a domain of study, research on the importance and role of metacognition in learning was developed. Introduced by Flavell (1976) and Brown (Brown, 1987), metacognition became a central construct in the field of Physics Education Research in the 1980s-1990s. A fundamental contribution was provided by the extensive work carried out by the researchers of Monash University in Australia (Gunstone, 1991, 1994; Gunstone & Mitchell, 1998; White & Gunstone, 1989). Metacognition, according to these researchers, refers to "the knowledge, awareness, and control of one's own learning" (Gunstone & Mitchell, 1998, p.135). In the light of the classical theory of conceptual change and its rational character, the relation between conceptual change and this definition of metacognition appears quite obvious given their interpretation of Posner et al.'s view of conceptual change: "The processes of recognizing existing conceptions, evaluating these, deciding whether to reconstruct, and reviewing are all metacognitive processes; they require appropriate *metacognitive knowledge, awareness, and control*." (Gunstone & Mitchell, 1998, p.137; Italics added). Metacognitive knowledge, awareness, and control are assumed to be learning outcomes and a great effort was devoted by these Australian researchers to designing teaching activities explicitly aimed to act at a metacognitive level(Gunstone & Mitchell, 1998). The outcomes of the activities were encouraging: the studies showed that metacognition *can* be promoted and *can* facilitate conceptual change. However, it also revealed shortcomings; metacognitive knowledge appeared fragile and artificial and students tended to perceive it as useful only to achieve their own short-term goals. In addition, it was not clear when, how, and why students activate the metacognitive knowledge necessary to manage their learning (Gunstone, 1991; White and Gunstone, 1989).

These problems, together with critiques of the classical model of conceptual change, led researchers to develop a progressively more complex picture of this layer of analysis on metacognitive knowledge and processes of relevance to conceptual change. This layer was gradually enriched with new approaches and theoretical constructs. In particular, two new themes emerged in the literature. In their edited volume, Sinatra and Pintrich (2003) collected contributions making the case for the role of learners' *intentions* in knowledge change and clarifying the importance of learner goals and motivations in conceptual change - i.e. understanding concept learning needs to go beyond the conceptual. Thus, the notion of *intentional conceptual change* began to include aspects associated with the notion of mindfulness, a "mid-level construct which reflects a voluntary state of mind, and connects among motivation, cognition and learning." (Salomon & Globerson, 1987, p. 623). A second development, influenced to a large extent by research in developmental psychology, was attention to learners' understanding of the nature of knowledge and knowledge change and justification, including scientific knowledge - what came to be referred to as "epistemic cognition." Researchers started to go beyond metacognitive awareness, evaluation and rational control, examining learners' understanding of the *nature of knowledge* and *of knowing* (Hofer and Pintrich, 1997), the a*ims*, i*deals*, and r*eliable processes* of learning (Chinn, Rinehart & Buckland, 2014), and to the *structure of physics knowledge,* the *content of physics knowledge,* the process of *learning physics* (Hammer, 1994).

In her review and synthesis of research on epistemic cognition, Smith (2018) shows how research has supported the view that sophisticated epistemic beliefs facilitate learning and conceptual change in multiple ways:

> by affecting what students attend to (e.g., underlying concepts and relations among ideas vs. surface form and isolated facts), what sources they value and trust (e.g., knowledgeable experts and data from well-designed studies vs. anecdote and personal experience), their motivation (e.g., high vs. low levels of effort and persistence), affective responses to conflict or uncertainty (e.g., interest and curiosity vs. avoidance and anxiety), and degree of metacognitive engagement. (Smith, 2018, p. 270)

But, as Smith also points out, the construct of "epistemic belief" has been criticized in Physics Education Research, when viewed from the perspective of Knowledge-in-Pieces. From this perspective, the notion of "epistemic belief" inherits some of the problems viewed as associated with a theory change perspective on conceptual change: - namely, like naive theories and beliefs, they are usually treated as "stable, robust cognitive structures corresponding to articulate, declarative knowledge [...] the units—the cognitive "atoms"—of epistemologies." (Louca, Elby, Hammer, Kagey, 2004, p.58).

Hammer and Elby (2002) have sketched an alternative view of naïve epistemologies from a *resources* perspective on knowledge and learning. Resources are viewed as knowledge elements of a finer grain size than *theories* or *beliefs*. Epistemological resources are to personal epistemologies what diSessa's p-prims are to intuitive physics. Like p-prims, young children are supposed to have multiple epistemological resources to think about physics knowledge and learning, which are activated in different ways in different contexts. In their framework, Hammer & Elby (2002; 2003) posit the existence of numerous metacognitive and epistemological resources, including those for understanding:

- *the source of knowledge* (Knowledge as transmitted stuff, Knowledge as fabricated stuff, Knowledge as free creation, and others)
- *forms of knowledge* (Story, Rule, Fact, Game, and others)
- *knowledge-related activities* (Accumulation, Formation, Checking, and others)
- *stances toward knowledge* (Acceptance, Understanding, Puzzlement, and others).

This framework also addresses the process of *activation* of these resources. A key construct for understanding activation within this framework is the notion of an epistemic frame. A "frame" is understood, phenomenologically, to be "a set of expectations an individual has about the situation in which she finds herself that affect what she notices and how she thinks to act" (Hammer, Elby, Scherr & Redish, 2005). Many aspects can be involved in an individual's or group's framing of a situation: some aspects are social ("Whom do I expect to interact with here and how?"); others are affective ("How do I expect to feel about it?"); and others are epistemological ("What do I expect to use to answer questions and build new knowledge?"). All these aspects can impact learning. For example, the cognitive dynamics can be very different if you, as a student, in a large lecture class, frame the situation as one in which you are expected to deliberate over what the professor says, or to record information (Hammer, Elby, Scherr & Redish, 2005).

This fine-grained perspective on the activation of epistemic resources increased the richness of analyses of the role of personal epistemology in learning and their influences on conceptual change. This perspective is currently being enriched even further. For example, Radoff, Jaber & Hammer (2019) point out the entanglement between the resources of epistemic cognition, meta-affective stances (feeling about feeling) and physics learning. They highlight the co-occurrence of epistemological beliefs about physics and feelings about being uncertain. For example, the epistemological belief that *physics is about absolute rights and wrongs* is entangled with the *anxiety about feeling uncertain,* the belief that *physics is about the journey and the question* is entangled with the meta-affective *comfort with feeling uncertain* and the epistemological belief that *doing physics is a process of making sense of the world* is entangled with forms of "*excitement about feeling uncertain*" (Radoff, Jaber & Hammer, 2019). Such results are likely to have great implications for teaching and teacher education (Elby & Hammer, 2010).

The theoretical research on metacognition, students' epistemologies and epistemic resources has had an important impact on practice. It has been used for instructional design (e.g., Hammer & Elby, 2003; Redish & Hammer, 2009) and it has oriented the production of important teaching resources in Physics Education Research. Some of them are surveys that can be used to recognise and measure students' self-reported beliefs about physics and learning expectations. Examples of these surveys include:: Colorado Learning Attitudes about Science Survey (CLASS) (Adams, Perkins, Podolefsky, Dubson, Finkelstein, & Wieman, 2006); Maryland Physics Expectations Survey (MPEX) and Epistemological Beliefs About Physics Survey (EBAPS) (Elby, 2001), Views About Science Survey (VASS) (Halloun & Hestenes, 1998); Colorado Learning about Science Survey for Experimental Physics (E-CLASS) (Zwickl, Hirokawa, Finkelstein & Lewandowski, 2014). Recommendations to administer these surveys have been also elaborated (Madsen, McKagan, Sayre, & Paul, 2019).

To come back to the theoretical thread of our chapter, we have seen in this section that an early interest in metacognition and its relevance to conceptual change has been enlarged to include attention learners' motivation and interests, their epistemic beliefs and resources, and even their affective stances and emotions associated with their personal epistemologies. Integrating these considerations into models of conceptual change, has "warmed" initially "cold" cognitive, overly rational, accounts of concept learning (Pintrich, 1999).

5. The Interplay between Conceptual Change and Identity Construction

In this section, we further broaden the viewpoint on conceptual change research. After focusing on research that illuminates learning processes as experienced by learners as self-aware epistemic agents, we shift the focus to considering research on how *particular* individuals, with their lived experiences, develop their understanding of physics content while developing their identities in relation to the discipline of physics.

Understanding the interaction between learning and identity formation has a particular urgency. Typical classroom dynamics, social norms, and distribution of power and authority in STEM disciplines (and physics, in particular) reinforce the image of a discipline that functions as an exclusive club, keeping out those from non-dominant and historically marginalized groups (Carlone, 2012). Contemporary research on identity makes visible how learning experiences in STEM classrooms are racialized (Hyater-Adams et al, 2018; McGee & Martin, 2011; Nasir & Shah, 2011) and gendered (Gonsalves, & Danielsson, 2020; Gosling & Gonsalves, 2020; Kalender et al., 2019; Traxler et al., 2016) and intersectional (Rosa & Mensah, 2016) in nature. Importantly, these recent studies contribute to an ongoing attempt to counter deficit-framings of the experiences of women, non-binary students, and students of color and, instead, highlight student agency and the engagement of their cultural, not just cognitive, resources. Despite the many studies in STEM education on identity, the particular intersection of identity and conceptual change has been limited. One of the reasons for this is probably that identity has been typically theorized, as a sociocultural phenomenon, using an analytical lense typically seen as at odds with conceptual change research traditions (Lave & Wenger, 1991). However, recently, some studies have shown that it is possible to use theoretical tools used to analyze conceptual change to reveal the interplay between these lines of work (Levin, Levrini, & Greeno, 2018).

Within the Knowledge-in-Pieces perspective, diSessa suggested that it is possible to transfer the theoretical and methodological apparatus he developed to study conceptual change to the study of identity (diSessa, 2018b). In doing so, he was particularly interested in how identity (which he takes to be similar to the notions of "self-concept" and "concept of others") is managed by individuals. Toward this goal, he focused analytic attention on the knowledge involved in learners forming characterizations of themselves and others. By "knowledge" here, diSessa worked in analogy with his definition of a coordination class as having a perceptual and inferential component: he was interested in what individuals attend to perceptually about themselves and others and what they infer based on this information (he calls them "characterizations" and "inferences" based on characterizations). As in his studies of conceptual change, diSessa pointed out the importance of inputs to the reasoning process that may not be articulated in words, but instead expressed through other modalities. In this context, he listed the feeling of joy or epiphany in participating in a scientific activity (or in contrast, feelings of revulsion towards other forms of activities or communities). While these sensations may be difficult to theorize about, diSessa highlighted their importance for understanding the development of individuals' relationships to the discipline and others in the discipline. Thus, diSessa's proposal for the nexus between identity and conceptual change is to use theoretical machinery that was built for studying the nature of knowledge and conceptual change processes to study the nature of identity and identity formation processes.

In aiming to explore the nexus between identity and conceptual change (the terrain focused on understanding the relationships between learning disciplinary content and becoming a particular kind of person) Levrini, Levin, and Fantini (2018; 2020) developed the holistic construct of "appropriation" (Levrini et al., 2015). This construct accounts for the ways in which students learning physics can situate themselves with respect to the disciplinary content they are learning. Through analyses of task-based interviews and classroom discourse, the researchers found that five discourse markers could be used to determine cases of students' learning experiences where students had made the content their own, inflected with their own tastes and purposes. Accordingly, appropriation involves different layers of learning, including conceptual, epistemological, metacognitive, and social layers. One implication of studying these features of student discourse is that a researcher can gain insight into how students are positioning themselves with respect to the discipline, with respect to the class and also with respect to their own personal narrative of who they are as a person and as a learner. Thus, the operational definition of appropriation provides a framework where disciplinary learning and identity can be compared and related. Identity formation can be viewed, from this perspective, positioning over time with respect to the discipline, class, and self (Levrini et al., 2018).

Beyond operationalizing appropriation, and related to our interest in this section of describing work at the nexus of identity formation and conceptual change, Levrini et al. (2018) contributed a particular way of thinking about the moment in conceptual change/learning where the individual is actually populating their understanding of scientific content with their personal tastes and purposes. This led them to introduce the notion of a *personal concept projection*, which is constructed around individuals' *signature ideas*. An example of a signature idea is "The distinction between becoming and being" used by a physics student interested in philosophy to populate the distinction between state and process variables with his tastes. Another example is "engines and how they work" used by another student to center the meaning of temperature on temperature gradient, since "this is what makes an engine work." The notion of personal concept projection is an enrichment of the model of coordination class, developed to model conceptual change (diSessa & Sherin, 1998) and introduces a locus in that theoretical model where an event contributing to identity formation can happen.

The nexus between identity and conceptual change is an area that is ripe for new research and is receiving more research attention (e.g., Heyd-Metzuyanim, 2018 for an approach based on the commognitive perspective). Where should the field go in trying to empirically and theoretically explore this terrain that pertains to both identity and conceptual change examined together? Appropriate methodologies to investigate the nexus between conceptual change and identity present several challenges. For instance, it is necessary to develop methodologies that are able to capture and blend together cognitive and social interactional aspects of learning and identity development (see diSessa, Levin & Brown, 2016 for an example of how analyses that blend cognitive and sociocultural assumptions can be operationalized).

Conclusions

In this chapter, we have taken a thematic and layered approach to reviewing the literature on conceptual change. Our motivation was to highlight the threads of this foundational area of research that are of historical interest for how the field of Physics Education Research has matured.

There is a tendency in educational research to "move past" earlier paradigms and perspectives. Instead, we offer an integrative view, arguing for the need to *not* conceptualize learning only at more macro levels, such as the level of epistemic practices or identity development, but instead to look for connections between these macro framings and theories of concepts and conceptual change. We arranged each of the sections in our review so as to highlight the possibilities for such connections.

To recap the terrain we have covered, we first examined how conceptual change research has conceptualized the very notion of concept and concept change at a functional level. That is, the work that the construct of "concept" does is meant to characterize how learners and scientists establish order in their understanding of the world. Different conceptualizations of "concept" have different entailments for processes of concept transformation and learning. The second layer unpacked in more detail how concepts are represented (using linguistic, mathematical, visual and gestural representations) and contrasted iconic/analogical versus propositional; and internal versus external representations and their roles in accounts of concepts and conceptual change. We then reviewed the interplay between epistemic practices and conceptual change – what do learners and scientists do with their knowledge and how do practices such as constructing explanations, models, and arguments activate knowledge resources? We then turned to reviewing literature that focused on the relationship between learners' metacognitive and epistemological ideas on the nature of knowledge and learning. In the final layer, we reviewed the literature that attends to the relationship between individuals' sense of themselves as learners and the cognitive processes involved in learning particular concepts.

In looking to the future of research in this area, we anticipate interesting theoretical and methodological developments in at least three directions: one is developments that ground accounts of conceptual change more firmly in what we understand about the brain and the body coming from the fields of neuroscience and embodied cognition; another is a more careful look at the interactions between internal mental and external representational tools; anda third is the development of ways to explore the nexus between conceptual change processes and epistemic practices, metacognition and identity. We believe that improving our understanding of connections between dimensions and across levels will have important implications for the design of learning environments and materials. It is only by tackling the theoretical challenge of understanding the many layers of the phenomenon of conceptual change and their interconnections that we will make practical progress in improving physics and more, generally, science learning in diverse and complex classroom settings.

References

Adams, W., Perkins, K., Podolefsky, N., Dubson, M., Finkelstein, N. & Wieman, C. . (2006). New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey, *Physical Review - Special Topics: Physics Education Research,* 2(010101) (2006).

Amin, T.G. (2009). Conceptual metaphor meets conceptual change. *Human Development*, 52, 165–197.

Amin, T. G. (2018). Representation, concepts and concept learning. In T. G. Amin & Levrini O. (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, (pp. 129 - 149). London and New York: Routledge.

Amin, T. G., Jeppsson, F., Haglund, J. (2015). Conceptual metaphor and embodied cognition in science learning (Special Issue). *International Journal of Science Education*, *37*(5-6), 745-991.

Amin, T. G., Jeppsson, F., Haglund, J. & Strömdahl, H. (2012). Arrow of time: Metaphorical construals of entropy and the second law of thermodynamics. *Science Education*, *95*(5), 818-848.

Amin, T. G. & Levrini O. (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routledge.

Amin, T. G., Smith, C. L., & Wiser, M. (2014). Student conceptions and conceptual change: Three overlapping phases of research. In N. Lederman & S. Abell (Eds.) *Handbook of research in science education*, *2* (pp. 57–81). London, UK: Routledge.

Barth-Cohen, L. A., & Wittmann, M. C. (2017). Aligning coordination class theory with a new context: Applying a theory of individual learning to group learning. *Science Education*, *101*(2), 333-363.

Barsalou, L. (2008). Grounded cognition. *Annual Review of Psychology*, *59*(1), 617–645.

Beeth, M. (1998). Teaching science in fifth grade: Instructional goals that support conceptual change. *Journal of Research in Science Teaching*, 35(10), 1091-1101

Beichner, R. (1994, August 1). Testing student interpretation of kinematics graphs. *American Journal of Physics*, 62(8), 750-62. Retrieved August 16, 2022, from https://doi.org/10.1119/1.17449

Besson, U. (2014). Teaching About Thermal Phenomena and Thermodynamics: The Contribution of the History and Philosophy of Science. In Michael R. Matthews (ed.), *International Handbook of Research in History, Philosophy and Science Teaching*. Springer. pp. 245-283.

Brookes, D.T., & E. Etkina, (2007). Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning. *Physical Review Special Topics: Physics Education Research*, 3(1), 1–16.

Brookes, D T. & Etkina, E. (2009). "Force," ontology, and language. *Physical Review Special Topics – Physics Education Research 5*, 010110. Brookes, D. T., & Etkina, E. (2015). The importance of language in students' reasoning about heat in thermodynamics processes. *International Journal of Science Education*, 37(5–6), 759–779

Brown, A. (1987). Metacognition, executive control, self-regulation and other more mysterious mechanisms. In: Weinert, F. and Kluwe, R. (Eds) *Metacognition, Motivation and Understanding*. Hillsdale, NJ: Erlbaum, pp. 65–116.

Brown, D. E. (2018). Implicit conceptual dynamics and students' explanatory model development in science. In Amin, T. G. & Levrini, O. (Eds.), *Converging Perspectives on Conceptual Change: Mapping an Emerging Paradigm in the Learning Sciences* (pp. 105-112). London: Routledge.

Brown, D. E., & Clement, J. (1989). Overcoming misconceptions via analogical reasoning: abstract transfer versus explanatory model construction. *Instructional Science*, *18*(4), 237–261.

Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.) *International handbook of research on conceptual change*, (pp. 127–154). London, UK: Routledge.

Carey, S. (1985). Are children fundamentally different types of thinkers and learners than adults? In S. Chipman, J. Segal, & R. Glaser (Eds.), *Thinking and learning skills* (Vol. 2, pp. 485–517). Hillsdale, NJ: Erlbaum. Reprinted by Open University Press: Open University Readings in Cognitive Development

Carey, S. (2009). *The Origin of Concepts.* Oxford University Press.

Carlone, H. B. (2012). Methodological considerations for studying identities in school science: An anthropological approach. In *Identity construction and Science Education Research* (pp. 7-25). Brill.

Chi, M.T.H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science: Minnesota studies in the philosophy of science* (pp. 129–186). Minneapolis: University of Minnesota Press.

Chi, M.T.H. (2005). Common sense conceptions of emergent processes. *Journal of the Learning Sciences*, *14*, 161–199

Chi, M. T. H. (2013). Two kinds and four sub-types of misconceived knowledge, ways to change it, and the learning outcomes. In Vosniadou, S. (Ed.), *International Handbook of Research on Conceptual Change* (pp. 48-70). Abingdon: Routledge

Chinn, C. A. (2018). Modeling, Explanation, Argumentation, and Conceptual Change. In Amin, T. G. & Levrini O. (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routledge, pp.206.

Chinn, C. A., Rinehart, R. W., & Buckland, L. A. (2014). Epistemic cognition and evaluating information: Applying the AIR Model of epistemic cognition. In D. N. Rapp & J. L. G. Braasch (Eds.), *Processing inaccurate information: Theoretical and applied perspectives from cognitive science and the educational sciences,* Cambridge, MA: MIT Press.

Clark, D. B. (2006). Longitudinal conceptual change in students' understanding of thermal equilibrium: An examination of the process of conceptual restructuring. *Cognition and Instruction, 24*(4), 467-563.

Clark, A., & Chalmers, D. (1998). The extended mind. *Analysis*, *58*(1), 7–19

Clark, D. B., D'Angelo, C. M., & Schleigh, S. P. (2011). Comparison of students' knowledge structure coherence and understanding of force in the Philippines, Turkey, China, Mexico, and the United States. *The Journal of the Learning Sciences*, *20*(2), 207-261.

Clark, D. B., & Linn, M. C. (2013). The knowledge integration perspective: Connections across research and education. In *International handbook of research on conceptual change* (pp. 532-550). Routledge.

Clement, J. (1988). Observed methods for generating analogies in scientific problem solving. *Cognitive Science*, *12*(4), 563–586. https://doi.org/https://doi.org/10.1016/0364-0213(88)90013-4

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, *11*(5), 554–565.

Close, H. & Scherr, R. (2015). Enacting conceptual metaphor through blending: Learning activities embodying the substance metaphor for energy. *International Journal of Science Education*, *37*(5-6), 839-86.

Crouch, C. & Mazur, E. (2001). Peer instruction: Ten years of experience and results, *American Journal of Physics*, 69 (9), 970.

Ding, L. (2007). *Designing an Energy Assessment to Evaluate Student Understanding of Energy Topics*, Ph.D., North Carolina State University.

diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens (Eds.), *Mental Models*. Hillsdale, NJ: Lawrence Erlbaum, 15-33.

diSessa, A. A. (1988). Knowledge in Pieces. In G. Forman and P. Pufall (Eds.), *Constructivism in the Computer Age*. Hillsdale, NJ: Lawrence Erlbaum, 49-70.

diSessa, A. A. (1993). Toward an Epistemology of Physics. *Cognition and Instruction*, *10*(2 & 3), 105–225.

diSessa, A. A. (1996). What do "just plain folk" know about physics? In D. R. Olson and N. Torrance (Eds.), *The Handbook of Education and Human Development: New Models of Learning, Teaching, and Schooling.* Oxford, UK: Blackwell Publishers, Ltd., 709-730.

diSessa, A. A. (2018a). A friendly introduction to "Knowledge in Pieces": Modeling types of knowledge and their roles in learning. In *Invited lectures from the 13th international congress on mathematical education* (pp. 65-84). Springer, Cham.

diSessa, A. A. (2018b). Identity and knowledge. in T. G. Amin & L. Levrini (Eds.). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routledge, p.297

diSessa, A. A (2022). A History of Conceptual Change Research: Threads and Faultlines. *Cambridge Handbook of the Learning Sciences.* Keith Sawyer (Ed.). *Cambridge University Press.*

diSessa, A. A., Levin, M. & Brown, N. J. S. (2016). *Knowledge and Interaction: A Synthetic Agenda for the Learning Sciences*. New York, NY: Routledge.

diSessa, A. A. & Sherin, B. L. (1998). What changes in conceptual change? *International Journal of Science Education*, *20*(10), 1155-1191.

diSessa, A., Sherin, B. & Levin, M. (2016). Knowledge Analysis: An Introduction. In A. A. diSessa, M. Levin & N.J.S. Brown (Eds.) *Knowledge and Interaction: A Synthetic Agenda for the Learning Sciences.* (pp. 30-71). Routledge. New York, NY.

diSessa, A. A., & Wagner, J. F. (2005). What coordination has to say about transfer. In J. Mestre (ed.), *Transfer of learning from a modern multi-disciplinary perspective* (pp. 121-154). Greenwich, CT: Information Age Publishing.

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of the literature related to concept development in adolescent science students. *Studies in Science Education*, 5, 61–84.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education*, 84(3), 287-312.

Duit, R. (2009). Bibliography–STCSE. Students' and Teachers' Conceptions and Science Education (http://www. ipn. uni-kiel. de/aktuell/stcse/download_stcse. html).

Duit, R., Goldberg, F. & Niedderer, H. (Eds.) (1992). *Research in physics learning: Theoretical issues and empirical studies*. Kiel, Germany: Institut fuir die Pidagogik der Naturwissenschaftenan der Universitit Kiel.

Duit, R. & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning, *International Journal of Science Education*, 25:6, 671-688

Elby, A. (2001). Helping physics students learn how to learn, *American Journal of Physics*, 69(7).

Elby, A., & Hammer, D. (2010). Epistemological resources and framing: A cognitive framework for helping teachers interpret and respond to their students' epistemologies. In L. Bendixen & F. Feucht (Eds.), *Personal Epistemology in the Classroom: Theory, Research, and Implications for Practice* (pp. 409-434). Cambridge: Cambridge University Press.

Erduran, S. & Jiménez-Aleixandre, M.P. (Eds.) (2007). *Argumentation in science education: Perspectives from classroom-based research,* (pp. 3-27). Dordrecht: Springer.

Euler, E., Rådahl, E., & Gregorcic, B. (2019). Embodiment in physics learning: A social-semiotic look. *Physical Review Physics Education Research*, *15*(1), 010134.

Fauville, G., Andersson-Lantz, A., Mäkitalo, Å., Dupont, S., & Säljö, R. (2016). The carbon footprint as a mediating tool in students' online reasoning about climate change. In O. Erstad, K. Kumpulainen, Å. Mäkitalo, K. Schrøder, P. PruulmanVengerfeldt, & T. Jóhannsdøttir (Eds.), *Learning across contexts in the knowledge society* (pp. 179–202). London: Sense.

Flavell, J. H. (1976). Metacognitive aspects of problem solving. In: Resnisk, L. B. (Ed) *The Nature of Intelligence*. Hillsdale, NJ: Lawrence Erlbaum, pp. 231–5.

Galili, I. (2021). *Scientific Knowledge as a Culture. The Pleasure of Understanding*. Springer Nature Switzerland.

Galili, I., & Bar, V. (1992). Motion implies force. Where to expect vestiges of the isconception? *International Journal of Science Education*, 14(1), 63–81.

Galili, I., & Hazan, A. (2000b). The influence of historically oriented course on students' content knowledge in optics evaluated by means of facets-schemes analysis. *Physics Education Research, American Journal of Physics*, 68(7), S3–S15.

Gentner, D., & Stevens, A. (1983). *Mental models.* Hillsdale, NJ: Erlbaum

Gilbert, J.K. (2004). Models and modelling: routes to more authentic Science education. *International Journal of Science and Mathematics Education,* 2(2), 115–130.

Gilbert, J.K., & Zylbersztajn, A. (1985). A conceptual framework for science education: The case study of force and movement. *International Journal of Science Education*, 7, 107-120.

Gonsalves, A. J., & Danielsson, A. T. (2020). Introduction: Why Do We Need Identity in Physics Education Research?. In *Physics Education and Gender* (pp. 1-8). Springer, Cham.

Gregorcic, B., Planinsic, G., & Etkina, E. (2017). Doing science by waving hands: Talk, symbiotic gesture, and interaction with digital content as resources in student inquiry. *Physical Review Physics Education Research*, *13*(2), 020104.

Gosling, C., & Gonsalves, A. J. (2020). Lessons from research exploring the underrepresentation of women in physics. *The Physics Teacher*, *58*(5), 342-344.

Gunstone, R. F. (1991). Constructivism and metacognition: theoretical issues and classroom studies. In: Duit, R., Goldberg, F. and Niedderer, H. (Eds) *Research in Physics Learning: Theoretical Issues and Empirical Studie*s. Bremen: IPN, pp. 129–40.

Gunstone, R. F. (1994). The importance of specific science content in the enhancement of metacognition. In: Fensham, P., Gunstone, R. F. and White, R. (Eds) *The Content of Science.* London: Falmer Press, pp. 131–46.

Gunstone, R., & Mitchell, I. J. (1998). Metacognition and Conceptual Change. In *Teaching Science for Understanding* (pp. 134 - 163). Academic Press.

Halloun, I. & Hestenes, D. (1998). Interpreting VASS dimensions and profiles for physics students, *Science Education* 7(6), 553–577.

Hammer, D. M. (1994). Epistemological beliefs in introductory physics. *Cognition and Instruction,* 12, 151–183.

Hammer, D. (1996). Misconceptions or P-Prims: How May Alternative Perspectives of Cognitive Structure Influence Instructional Perceptions and Intentions?. *The Journal of the Learning Sciences*, Vol. 5, No. 2 (1996), pp. 97-127, Taylor & Francis, Ltd.

Hammer, D., & Elby, A. (2002). On the form of a personal epistemology. In *Personal epistemology: The psychology of beliefs about knowledge and knowing*, *169- 190*.

Hammer, D. & Elby. A. (2003). Tapping Epistemological Resources for Learning Physics, *Journal of the Learning Sciences*, 12:1, 53-90.

Hammer, D., Elby, A., Scherr, R.E., & Redish, E.F. (2005). Resources, framing, and transfer. In J. Mestre (Ed.). *Transfer of Learning: Research and Perspectives*. Greenwich, CT, Information Age Publishing.

Henderson, J. B., Langbeheim, E., & Chi, M. T. (2018). Addressing robust misconceptions through the ontological distinction between sequential and emergent process. In Amin, T., & Levrini, O. (Eds.), *Converging Perspectives on Conceptual Change: Mapping an Emerging Paradigm in the Learning Sciences*. (pp. 26-33). Milton: Routledge

Hestenes, D., Wells, M., and Swackhamer, G. (1992). Force Concept Inventory, *The Physics Teacher* 30, 141-151

Hewson, P. & Hennessey, M. G. (1992). Making status explicit: A case study of conceptual change In R. Duit, F. Goldberg, & H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 176 - 187). Kiel, Germany: Institut fuir die Pidagogik der Naturwissenschaftenan der Universitit Kiel.

Heyd-Metzuyanim, E. (2018). A discursive approach to identity and critical transitions in mathematics learning. In T. Amin & O. Levrini (Eds.), *Converging Perspectives on Conceptual Change* (pp. 289–296). Routledge.

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research*, 67, 88-140.

Hutchins, E. (1995). *Cognition in the Wild*. MIT press.

Hyater-Adams, S., Fracchiolla, C., Finkelstein, N., & Hinko, K. (2018). Critical look at physics identity: An operationalized framework for examining race and physics identity. *Physical Review Physics Education Research*, *14*(1), 010132.

Jeppsson, F., Haglund, J., Amin, T., & Strömdahl, H. (2013). Exploring the use of conceptual metaphors in solving problems on entropy. *Journal of Learning Sciences*, 22(1), 70–120

Jiménez-Aleixandre, M.P. & Broco, P. (2018). Shifts in Epistemic Status in Argumentation and in Conceptual Change. In Amin, T. G. & Levrini O. (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routledge, pp.171.

Jiménez-Aleixandre, M.P., & Erduran, S. (2007). Argumentation in science education: An overview. In S. Erduran & M.P. Jimenez-Aleixandre (Eds.), *Argumentation in science education: Perspectives from classroom-based research* (pp. 3-27). Dordrecht: Springer.

Johnson-Laird, P. (1983). *Mental models*. Cambridge: Cambridge University Press.

Justi, R. & Gilbert, J. (2003). Teachers' views on the nature of models, *International Journal of Science Education*, 25:11, 1369-1386, DOI: 10.1080/0950069032000070324

Kalender, Z. Y., Marshman, E., Schunn, C. D., Nokes-Malach, T. J., & Singh, C. (2019). Gendered patterns in the construction of physics identity from motivational factors. *Physical Review Physics Education Research*, *15*(2), 020119.

Kapon, S. (2017). Unpacking Sensemaking. *Science Education*, *101*(1), 165–198. https://doi.org/10.1002/sce.21248

Kapon, S. & Berland, L. (2022). Epistemic models of sensemaking and reasoning. In M. F. Taşar & P. Heron (Eds.). *International Handbook of Physics Education Research* (IHPER).

Kapon, S., & diSessa, A. A. (2012). Reasoning through instructional analogies. *Cognition and Instruction*, *30*(3), 261–310. https://doi.org/10.1080/07370008.2012.689385

Koponen, I.T. (2007). Models and Modelling in Physics Education: A Critical Re-analysis of Philosophical Underpinnings and Suggestions for Revisions. *Science & Education*, 16(7–8), 751–773.

Koponen, I. T. (2014). Introduction: Conceptual Change and Its Models. *Science & Education* 23, 1411–1412 (2014).

Kuhn, T. (1962). *The structure of scientific revolutions.* Chicago: University of Chicago Press.

Kuhn, T. (1977). *The essential tension: Selected studies in scientific tradition and change*. Chicago: University of Chicago Press

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago: University of Chicago Press

Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and the challenge to Western thought*. New York: Basic Books

Lambert, C. (2012). Twilight of the Lecture. *Harvard Magazine.* https://www.harvardmagazine.com/2012/03/twilight-of-the-lecture;

Larkin, J. H. & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65–99.

Lave, J., & Wenger, E. (1991). *Situated learning: Legitimate peripheral participation*. Cambridge University Press.

Lehrer, R., & Schauble, L. (2015). The development of scientific thinking. In L. S. Liben, U. Müller, & R. M. Lerner (Eds.), *Handbook of child psychology and developmental science: Cognitive processes* (pp. 671–714). John Wiley & Sons, Inc.

Lehrer, R., Schauble, L., Strom, D., & Pligge, M. (2003). Similarity of form and substance: Modeling material kind. In D. Klahr & S. Carver (Eds.), *Cognition and Instruction: 25 years of progress*, (pp. 39–74). Mahwah, NJ: Erlbaum.

Lemke, J. (1990). *Talking science: Language, learning and values*. Ablex Publishing.

Lemke, J. (1998). Teaching all the languages of science: Words, symbols, images and actions. Paper presented at *Conference on Science Education*, Barcelona.

Levin, M., Levrini, O., & Greeno, J. (2018). Unpacking the nexus between identity and conceptual change: Perspectives on an emerging research agenda. In T. Amin and O. Levrini *Converging perspectives on conceptual change* (pp. 313-333). Routledge.

Levrini O., diSessa A.A. (2008). How Students Learn from Multiple Contexts and Definitions: Proper Time as a Coordination Class. *Physical Review Special Topics - Physics Education Research* 4, 010107.

Levrini, O., Fantini, P., Tasquier, G., Pecori, B., & Levin, M. (2015). Defining and operationalizing appropriation for science learning. *Journal of the Learning Sciences*, 24(1), 93-136.

Levrini, O., Levin, M., & Fantini, P. (2018). Personal, deeply affective, and aesthetic engagement with science content: when disciplinary learning becomes a vehicle for identity construction. In T. Amin & O. Levrini, *Converging perspectives on conceptual change* (pp. 305-312). Routledge.

Levrini, O., Levin, M., & Fantini, P. (2020). Fostering appropriation through designing for multiple access points to a multidimensional understanding of physics. *Physical Review Physics Education Research*, 16(2), 020154.

Levrini, O., Levin, M., Fantini, P., & Tasquier, G. (2019). Orchestration of classroom discussions that foster appropriation. *Science Education*, 103(1), 206-235.

Limon, M. & Mason, L. (eds.) (2002), *Reconsidering conceptual change: issues in theory and practice*, Dordrecht, The Netherlands: Kluwer Academic.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researche*r, *42*(8), 445–452

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016) Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers and Education*, *95*, 174–187

Linn, M. C., & Eylon, B. S. (2011). *Science learning and instruction: Taking advantage of technology to promote knowledge integration*. Routledge.

Linn, M., Eylon, B. S., Kidron, A., Gerard, L., Toutkoushian, E., Ryoo, K., ... & Laurillard, D. (2018). Knowledge integration in the digital age: Trajectories, opportunities and future directions. *International Society of the Learning Sciences*, Inc.[ISLS].

Louca, L., Elby, A., Hammer, D., & Kagey, T. (2004). Epistemological Resources: Applying a New Epistemological Framework to Science Instruction. *Educational Psychologist*, 39(1), 57–68.

Madsen, A., McKagan, S. B., Sayre, E. C. & Paul, C. A. (2019). Resource Letter RBAI-2: Research-based assessment instruments: Beyond physics topics, *American Journal of Physics*. 87, 350.

McDermott, L.C., & Shaffer, P.S., University of Washington - Physics Education Group (2’12). *Tutorials in Introductory Physics*. Pearson.

McGee, E. O., & Martin, D. B. (2011). “You would not believe what I have to go through to prove my intellectual value!” Stereotype management among academically successful Black mathematics and engineering students. *American Educational Research Journal*, 48(6), 1347-1389.

Millar, R., & Osborne, J. (Eds.) (1998). *Beyond 2000: Science education for the future (the report of a seminar series funded by the Nuffield Foundation)*. London: King’s College London.

Minstrell, J. (1992). Facets of students' knowledge and relevant instruction. In R. Duit, F. Goldberg & H. Niedderer (Eds.), *Research in physics learning: Theoretical issues and empirical studies* (pp. 110-128). Kiel, Germany: Institut fuir die Pidagogik der Naturwissenschaftenan der Universitit Kiel.

Nasir, N. I. S., & Shah, N. (2011). On defense: African American males making sense of racialized narratives in mathematics education. *Journal of African American Males in Education* (JAAME), 2(1), 24-45.

Nersessian, N.J. (1987). A Cognitive-Historical Approach to Meaning in Scientific Theories. In: Nersessian, N.J. (eds) *The Process of Science. Science and Philosophy*, vol 3. Springer, Dordrecht.

Nersessian, N. J. (1989). Conceptual change in science and in science education. *Synthese*, 80(1), 163-183.

Nersessian, N. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In. R. Giere (Ed.), *Cognitive models of science* (pp. 3–44). Minneapolis: University of Minnesota

Nersessian, N. J. (2008). *Creating Scientific Concepts*. MIT Press, Cambridge, MA, ISBN: 978-0-262-14105-5, 251 pp.

Neumann, K., Viering, T., Boone, W. & Fischer, H. (2012). Towards a learning progression of energy, *Journal of Research in Science Teaching* 50 (2), 162.

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states (vol. 1, The Standards)*. Washington, DC: The National Academies Press.

Pea, R. D. (1994). Seeing what we build together: Distributed multimedia learning environments for transformative communications. *Journal of the Learning Sciences*, 3(3), 285–299.

Piaget, J. (1954). *The construction of reality in the child.* New York: Basic Books

Pintrich, P. R. (1999). Motivational beliefs as resources for and constraints on conceptual change. In W. Schnotz et al. (Eds.), *New perspectives on conceptual change* (pp. 33–50). Amsterdam: Pergamon.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, *66*, 211–227.

Radoff, J., Jaber, L. Z., & Hammer, D. (2019). "It's Scary but It's Also Exciting": Evidence of Meta-Affective Learning in Science. *Cognition and Instruction,* 37(1), 73-92.

Redish, E.F. & Hammer, D. (2009). Reinventing college physics for biologists: Explicating an Epistemological Curriculum, *American Journal of Physics*, 77. 629-642.

Robinson, S., Otero, V. & Goldberg, F. (2010). Design principles for effective physics instruction: A case from physics and everyday thinking, *American Journal of Physics*, 78 (12), 13.

Rosa, K., & Mensah, F. M. (2016). Educational pathways of Black women physicists: Stories of experiencing and overcoming obstacles in life. *Physical Review Physics Education Research*, *12*(2), 020113.

Roschelle, J. (1992). Learning by collaborating: Convergent conceptual change. *Journal of the Learning Sciences*, *2*(3), 235–276.

Roth, W-M. (2001). Gestures: Their role in teaching and learning. *Review of Educational Research*, *71*, 365- 392.

Roth, W-M. & Lawless, D. V. (2002). Scientific investigations, metaphorical gestures, and the emergence of abstract scientific concepts. *Learning and Instruction*, *12*, 285-304.

Rusanen, A-M. & Pöyhönen, S. (2013). Concepts in Change. *Science & Education* 22 (6):1389-1403.

Säljö, R. (2018). Conceptual change, materiality and hybrid minds. In Amin, T. G. & Levrini, O. (Eds.), *Converging Perspectives on Conceptual Change: Mapping an Emerging Paradigm in the Learning Sciences* (pp. 113-120). London: Routledge.

Salomon, G., and Globerson, T. (1987) Skill may not be enough: the role of mindfulness in learning and transfer. *International Journal of Educational Research*, 11, 623–637.

Scherr, R. E. (2008). Gesture analysis for physics education research. *Physical Review - Special Topics: Physics Education Research.* 4(1), 1-9.

Schnepps, M. H., and Sadler, P. M. 1989, *A Private Universe—Preconceptions that Block Learning [videotape]*, Cambridge, MA: Harvard-Smithsonian Center for Astrophysics.

Schnotz W, Vosniadou S, Carretero M (eds) (1999). *New perspectives on conceptual change*. Pergamon, Oxford UK.

Schoultz, J., Säljö, R., & Wyndhamn, J. (2001). Heavenly talk: Discourse, artifacts, and children's understanding of elementary astronomy. *Human Development,* 44, 103–118

Schwarz, C., & White, B. (2005). Meta-modelling knowledge: Developing students' understanding of scientific modelling. *Cognition and Instruction, 23*(2), 165–205.

Scott, P. H., Asoko, H. M. and Driver, R. H. (1992). Teaching for conceptual change: a review of strategies. In Duit, R., Goldberg, F. and Niedderer, H. (Eds) *Research in Physics Learning: Theoretical Issues and Empirical Studies*. Bremen: IPN, pp. 310–29.

Sherin, B. L. (2001). How students understand physics equations. *Cognition and instruction*, *19*(4), 479-541.

Sherin, B. (2006). Common sense clarified: The role of intuitive knowledge in physics problem solving. *Journal of Research in Science Teaching*, *43*(6), 535-555.

Sherin, B. (2018). Elements, Ensembles, and Dynamic Constructions. In Amin, T. G. & Levrini O. (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routlege, pp.351.

Sinatra, G. M., and Pintrich, P. R. (Eds.) (2003). *Intentional conceptual change*. Mahwah, NJ: Erlbaum.

Singh, C. & Rosengrant, D. (2003). Multiple-choice test of energy and momentum concepts, *American Journal of Physics,* 71 (6), 607.

Slotta, J.D., & Chi, M.T.H., & Joram, E. (1995). Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction*, *13*(3), 373–400.

Smith, C. (2007). Bootstrapping processes in the development of students' commonsense matter theories. *Cognition and Instruction*, *25*(4), 337–398.

Smith, C. L. (2018). Conceptualizing the interactions among epistemic thinking, metacognition, and content specific conceptual change. In T. G. Amin, & O. Levrini (Eds) (2018). *Converging Perspectives on Conceptual Change. Mapping an Emerging Paradigm in the Learning Sciences*, London and New York: Routledge, pp.268.

Smith, C. L. & Amin, T. G. (forthcoming). The cognitive foundations of science learning progressions.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition*, *21*(3), 177-237.

Smith, C., Snir, J., & Grosslight, L. (1992). Using conceptual models to facilitate conceptual change: The case of weight-density differentiation. *Cognition and Instruction*, 9(3), 221–283.

Smith, C. & Unger, C., (1997). What's in dots-per-box? Conceptual bootstrapping with stripped down visual analogs. *Journal of the Learning Sciences*, 6(2), 143-181.

Sokoloff, D. & Thornton, R. (1997). Using interactive lecture demonstrations to create an active learning environment, *Physics Teacher,* 35 (6), 340.

Strike, K.A., & Posner, G.J. (1985). A conceptual change view of learning and understanding. In L.H. West & A.L. Pines (Eds.), *Conceptual structure and conceptual change* (pp. 189–210). Orlando, FL: Academic Press, Inc.

Strike, K.A., & Posner, G.J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.). *Philosophy of science, cognitive psychology, and educational theory and practice (pp. 147–174)*. Albany: State University of New York Press

Tarsitani, C. & Vicentini, M. (1991). *Calore, energia, entropia*. Roma: Franco Angeli.

Tasquier, G., Levrini, O. & Dillon, J. (2016) Exploring students' epistemological knowledge of models and modelling in science: results from a teaching/learning experience on climate change, *International Journal of Science Education,* 38:4, 539-563.

Traxler, A. L., Cid, X. C., Blue, J., & Barthelemy, R. (2016). Enriching gender in physics education research: A binary past and a complex future. *Physical Review Physics Education Research*, *12*(2), 020114.

Viennot, L. (2001). *Reasoning in physics* (chap. 5). Dordrecht: Kluwer

Vosniadou, S. (2013). Conceptual change in learning and instruction: The framework theory approach. In *International Handbook of Research on Conceptual Change* (2nd ed., pp. 11-30). Routledge.

Vosniadou, S., & Brewer, W. E. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, *24*(4), 535–585.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, 9(4), 625–636.

Wiser, M. (1987). The differentiation between heat and temperature: History of science and novice-expert shift. In S Strauss (Ed.), *Ontogeny, phylogeny, and historical development.* Norwood, N.J.: Ablex.

Wiser, M. (1995). Use of history of science to understand and remedy students' misconceptions about heat and temperature. In D.N. Perkins, J.L. Schwartz, M.M. West, & M.S. Stone (Eds.), *Software goes to school* (pp. 23–38). New York: Oxford University Press.

Wiser, M., & Amin, T. (2001). "Is heat hot?" Inducing conceptual change by integrating everyday and scientific conceptions. *Learning and Instruction*, 11, 331–355.

Wiser, M., & Amin, T.G. (2002). Computer-based interactions for conceptual change in science. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 357–387). Dordrecht, the Netherlands: Kluwer

Wiser, M. & Smith, C. (2016). How is conceptual change possible? Insights from science education. In D. Barner & A.S. Baron (Eds.) *Core knowledge and conceptual change* (pp. 29-51). Oxford: Oxford University Press.

Wittmann, M. C. (2002). The object coordination class applied to wave pulses: analysing student reasoning in wave physics. *International Journal of Science Education*, 24(1), 97-118.

Whitaker R. J (1983). Aristotle is not dead: Student understanding of trajectory motion. *American Journal of Physics* 51, 352 (1983); https://doi.org/10.1119/1.13247

White, B.Y. (1993). ThinkerTools: Causal Models, Conceptual Change, and Science Education. *Cognition and Instruction*, 10(1), 1–100

White, R. T. and Gunstone, R. F. (1989). Metalearning and conceptual change, *International Journal of Science Education*, 11, Special Issue, 577–86.

Zwickl, B. M., Hirokawa, T., Finkelstein, N. & Lewandowski, H. J. (2014). Epistemology and expectations survey about experimental physics: Development and initial results, *Physical Review - Special Topics: Physics Education Research,* 10(010120).