Conceptual Change in Cognitive Science Education - towards Understanding and Supporting Multidisciplinary Learning

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Abstract

Entering into higher education, students' conceptions undergo a restructuring process. When this reorganization is comprehensive, it is called "conceptual change". In this paper, a framework for discipline-based research into student conceptions and learning in cognitive science education is presented, in which conceptual differentiation is taken to be the key to conceptual change in learning cognitive science. Commonsense concepts are seen as loosely organized clusters of features without unified, coherent logical structure, but already containing, in embryonic form, the basic thought patterns out of which the scientific conceptions are constructed. This construction process requires that the student first differentiates or abstracts the right conceptual elements (both in terms of contexts of application , terminology associated with them, and the inferential patterns they enter into), and then organizes them into definite schemata in which conceptual relations are based on theoretical definitions, rather than situational cues or associations. The special requirements of a multidisciplinary science and empirical, and educational implications of the focus on differentiation are discussed.

Introduction

When students enter university education for the first time, their conceptions of various phenomena in a domain undergo (or at least are hoped to undergo) a restructuring process, leading from commonsense belief (naive physics, folk psychology) to scientific conceptions. When this reorganization is comprehensive enough to affect ontological commitments, inferential relations, the domain and standards of explanation - even the individuation of core concepts in the domain, it is called conceptual change (Carey, 1985; Hewson, 1984; Strike & Posner, 1982).

Conceptual change does not occur spontaneously, however. Nor is it enough that the scientific conceptual framework and patterns of thought are made available to students in clearly presented form. This is because students enter higher education with a rich and robust array of conceptions - some of them misconceptions - and a commonsense conceptual framework within which they interpret and make sense of instruction (Caramazza et al., 1981; McCloskey, 1983). These student conceptions are a source of resilience to influence by instruction and confusion. But they are also the seeds of scientific conceptions (if the basic thought patterns of the expert were not already present in some rudimentary and undisciplined form in the novice, acquisition of expertise in the discipline would appear altogether mysterious).

From a theoretical point of view, acquisition of expertise must be seen as a transformation of the initial state of the novice to the final state of the expert. Characterization of the initial state of this process is a necessary prerequisite. From a practical point of view, instruction must be adapted to what the student is able to receive (where they are on the novice-to-expert trajectory). We ignore student preconceptions at our peril.

In this paper, a framework for understanding student conceptions and learning in cognitive science education is presented. Some practical implications and the special requirements the multidisciplinarity of cognitive science places on the student and instructor are discussed briefly.

Cognitive Science Education

The outlook in this paper is that of discipline-based research. This differs from traditional research in higher education in that the focus is on (development of) student understanding of specific concepts, rather than learning in general, or individual differences in students that affect learning outcome. The approach is by far most developed in the context of physics education (see McDermott & Redish, 1999).

Such research is most naturally carried out by researchers and teachers working within the field in question. As McDermott (1991) notes, “Physicists are much more likely than science educators or cognitive psychologists to be able to explore student understanding of physics in depth”. But in this regard, cognitive science is in a unique position. Since cognitive science is the discipline within whose domain the empirical study of concepts (and hence conceptual change) most naturally falls, cognitive scientists should have the best of both worlds, i.e. theoretical understanding of concept development *and* an in depth understanding of the theories cognitive science students are expected to master.

Therefore, it is somewhat surprising that to date very little discipline-based research into student conceptions and conceptual change in learning cognitive science has been carried out. By far the greatest bulk of discipline based research to date has been carried out within the discipline of physics. Also most of cognitive science on conceptual change centers on learning and problem solving in physics. On the other hand, the fragmented theoretical landscape - compared to that of basic physics - and the controversy even among experts of the appropriate definition of key concepts such as representation, information or language - makes this perhaps less surprising.

Much of the research on learning physics should generalize into other disciplines, including Cognitive Science. However, as a discipline Cognitive Science has some unique features as well. These stem from the multidisciplinary nature of the discipline, and the fact that as sciences go, Cognitive Science is a relative newcomer.

In established sciences, most notably basic physics, the underlying logic of the theories - basic concepts and the dependence of more specialized fields on a common core - is thoroughly worked out and agreed upon. In cognitive science, even the appropriate definition of it (arguably!) most fundamental concepts are matters of philosophical debate (concepts such as knowledge, learning, innateness, computation, information, mind...).

There are few established "first principles" in cognitive science proper. Neighboring disciplines (computer science and AI, linguistics, to a lesser extent neuroscience, psychology and philosophy) do have fundamental concepts and basic principles to derive specific instances from, but this creates its own difficulties for the student. They face a bewildering array of technical and semi-technical terminology stemming, historically, from various sources in different disciplines; often the underlying concept for a given term is subtly different in meaning and application, depending on which discipline a particular theory or foundational approach is most closely associated with. All too often interpreting a term used in one context from the point of view of another leads to inconsistency and confusion.

Instructors involved in curriculum design face the complementary problem of depth and breadth of coverage. Given that cognitive science majors cannot be expected to acquire all the same competences as computer science majors and linguistics majors and neuroscience majors and...what are the appropriate standards of student assessment? What level of theoretical understanding and thought processes (problem solving, experimental design...) in information theory, psychophysics, or logic and linguistics should we expect from students of cognitive science, for example? The answer on gives to these questions depends in part on one's theoretical understanding of what kind of learning is involved in acquiring competence in problem solving and mastering the concepts of these disciplines, and their integration into a coherent cognitive science framework.

Differentiation by Abstraction as Key to Conceptual Change

“Conceptual change” is a somewhat blurry cover term, often used to denote global change in a conceptual framework (Chi & Roscoe, 2002; Duit, 1999). When applied to individual learning it is taken to entail some kind of wholesale reconstruction of one's theoretical outlook on a domain (Carey 1985, 1991). In this paper, “conceptual change” refers the process off overcoming the divide between commonsense conceptions and scientific theories. (Which is taken to be a different form of conceptual change from conceptual development in childhood and adolescence, i.e. the spontaneous emergence of commonsense conceptions and intuitive theories, including our naïve theory of mind). A change in concepts is involved insofar as the (literal) meaning associated with words used to describe the domain changes.

There are differences between acquisition of commonsense and scientific theories in both process and outcome. As for process, acquisition of commonsense conceptions occurs relatively spontaneously and uniformly, based on everyday experience and relatively little explicit instruction - whereas conceptual change in higher education requires considerable conscious effort, external support, and ingenuity on the part of the instruction. (Indeed, research on student conceptions in physics education has shown time and time again how a relatively small percentage of students acquires a deep conceptual understanding of the scientific theories they are exposed to). In terms of outcome, scientific knowledge differs from commonsense conceptions and folk "theories" in terms of both the systematicity of its organization and the disciplined manner it is applied to specific instances.

As the student undergoes the cognitive transformation associated with learning a new scientific theory, theoretical terms acquire new, sharp, “technical” meanings where there previously were just undisciplined connotations and where the interpretation of phenomena was previously interpreted in terms of loosely organized associations cued by surface features and specific contexts interpretations now become based on basic concepts (in the form of schematic representations governed by the formal structure of the theory).

The view of conceptual change in science students, especially cognitive science students developed here builds on research on conceptual change in physics (e.g. Chi, 1981; DiSessa, 1988, 1993; Larkin, 1983; Larkin et al., 1980; Wiser & Carey, 1983). Especially relevant is Carey's idea of differentiation (Carey, 1985, 1991; Wiser & Carey, 1983). Carey suggests conceptual change to come about by way of three processes of reorganization, which can be characterized by analogy from examples in the history of science: replacement (which like the replacement of the concept of phlogiston by the concept oxygen in theories of combustion), coalescence (as in Galileo's reinterpretation of the aristotelian distinction between natural and violent motions as a distinction without a difference in his development of a unified concept of motion), and differentiation (as in Black's differentiation of hotness/coldness into temperature and heat, See Wiser & Carey, 1983).

What kind of differentiation might best characterize conceptual change in science learning? This differentiation results not just in several categories where there previously were one: instead, a qualitative shift in the organization of knowledge from commonsense into theoretical must also be involved. This is in distinction to especially conceptual change in childhood, where the outcome is a commonsense theory, but also to conceptual change (paradigm shift) in science, where the point of origin the initial state - is also a scientific theory. (To the extent the original theory is much cruder, qualitative than the successor, "pre-paradigmatic", the historical case gives better and better approximation of the individual case.

The key difference is the kind of differentiation at play. Straightforward "splitting of concepts" differentiation does not yet lead from unscientific to scientific conceptions. What is instead crucial is that the student abstract from their intuitive commonsense concepts the (few) features which will come to form basic concepts around which the emerging scientific conception will be built. By "features" I mean basic conceptual elements which can be identified or recognized in different contexts, and patterns of inference related to them. They can be "cued" by the situation or "recognized" by the individual as recurring patterns in surface features of situations, and are used in categorizing, reasoning about, and making sense of everyday experience and interpreting reports of it made by other people (including instructors). However, in distinction to the respective scientific concepts, they have no clear definitions, no definite operational criteria of application, and, most of all, the way they are organized together into commonsense concepts lacks the systematicity of formal theories in the sciences.

The commonsense concept can be considered as a loosely organized cluster of features (connotations of the corresponding term, if you will). These features may be organized into schemata that fit specific phenomena for interpretation, but this organization is haphazard and sensitive to specific context. It is not "deep" in the sense of being governed by an understanding of first principles.

What I have in mind, then, is something along the lines of DiSessa's (1988, 1993) "knowledge in pieces" account of the incoherent nature of commonsense conceptions. DiSessa (ibid.) has attempted to define and tabulate some of the elements involved in our intuitive understanding of mechanics and mechanisms generally, which will then form the core of later scientific theories, though his "p-prims" are probably meant to be lower level elements than what is meant here by "features"). The features themselves need not be full-blown concepts. At least they are generally not themselves meanings of the terms used to describe a domain - typically, the student would not have easy access to a verbal expression of them - either via name or definite description.

Admittedly, not all commonsense concepts have a term associated with them, either. For example the commonsense concept IMPETUS seems to underlie many patterns of misinterpretation and misconception in learning mechanics (Caramazza et al., 1981; McCloskey, 1983), and therefore it is inferred to "be there", in the form of an ontological assumption of the student of *something* being given to a projectile when "impelled", and this something is not momentum or kinetic energy in the scientific sense. Yet "impetus" is not so denoted in most subjects' vocabulary. Instead they may speak of "push", "force", or "speed" given to a projectile and gradually dying away - these terms are equivocally used for other concepts as well, e.g. "speed" for SPEED.

Differentiation then leads from IMPETUS-based theory to a scientific conception which schematizes phenomena in terms of SPEED, VELOCITY, FRAMES OF REFERENCE, ACCELERATION, FORCE, MOMENTUM, KINETIC ENERGY, WORK etc. What is involved is not a wholesale *rejection* of the features and relations that make up the commonsense (mis)conception, but abstraction of certain features and relations as the "legitimate" ones, and construction of a scientific conception.

In learning a theory, some of the features associated with the commonsense concepts will be compatible with the scientific theory, and will be reorganized to form scientific concepts. Others will not. What is more, when a scientific conception is constructed, the elements will receive the status of full concepts. In effect, they will come to constitute the "technical" meaning of terms in the theory. Also, the patterns of inference will then be governed by the formal structure of the theory. This does not mean the expert would always work formally and from first principles, instead, expert performance seems to depend on powerful qualitative schemata of representation and reasoning (Chi et al., 1981, 1982; Larkin et al., 1980; Larkin, 1983; VanHeuvelen, 1991). What I mean by their being governed by the theory is that - unlike commonsense misconceptions - the paths of qualitative reasoning lead to legitimate conclusions and can be refined or interpreted in terms of more formal representations.

This is what is meant here by differentiation *by abstraction*, then: the right features must be differentiated or abstracted from their host commonsense concept clusters (bound by loose association based on experience), and reorganized into a new scientific concept (or a systematic cluster of interdefined concepts), so that after completion all the inferential licences afforded by the theory are recognized - and only those. The intuitive plausibility jumping to theoretically unwarranted conclusions will carry no weight after conceptual change has occurred (whereas untutored common sense trades almost exclusively on intuitive plausibility, which in turn depends on "interpretation" of the concept in question (this can in turn be considered to be salience, in context, of particular features).

Implications for Cognitive Science Education

Having characterized in broad outline the general framework for understanding conceptual change, I now turn to the implications of this framework to instruction and assessment in cognitive science, and discipline-based research in cognitive science.

The first implication is that instruction and assessment should be sensitive to students' ability to differentiate concepts. This is especially important in a multidisciplinary science, where many of the basic concepts are borrowed from established theories in already established disciplines. The student should at the outset be made sensitive to the fact that terms such as "learning" or "inference", even "computation", have both various connotations (not all of which will apply in any particular context), and different technical meanings for computer scientists, neuroscientists and philosophers. What is more, students' ability to differentiate should be emphasized in instruction and assessment. If student conceptions, especially the inferential licences they take specific concepts to invoke, are not explicitly probed, major confusion may go unnoticed (as the instructor interprets students' use of terms from the point of view of their own conceptual framework, rather than the student's).

Care should be taken to ensure students recognize homonymous use of terms, and are able to "keep track" of the interpretation and inferential role of a concept within the framework of a specific theory. If confusion in these basic issues is not diagnosed and addressed from the beginning, confusion is bound to result. This means, that instructional materials should be designed so that they explicitly address the need of the student to be able to differentiate between different interpretations of terms (and their relation to commonsense conceptions).

Take, for example, the concept INNATENESS. The commonsense term “innate” has a variety of biological and psychological connotations. For example, Mameli and Bateson's (2006) philosophical analysis reveals twenty-six different and sometimes mutually incompatible definitions for the commonsense concept. (They conclude that the commonsense concept probably does not have a unique scientific counterpart concept, a conclusion which under the present assumption makes sense). In neuroscience, philosophy, developmental psychology and behavioral genetics the term is used in decidedly differing meanings. However, if neuroscientists in neuroscience textbooks generally present one interpretation, philosophers another and geneticists yet a third, it is left to the student to figure out the interrelations (either that or decide to stick within the confines of a single discipline). The lesson here is that, if indeed differentiation by abstraction is crucial to learning cognitive science concepts, multidisciplinary study materials explicitly contrasting these and forcing the student to do so as well are needed (it does not do to expect most students to perform this feat of abstraction themselves).

Second, since the claim is that the misconception is the father of the science (as the child is said to be the father to the man), then the implication is that instruction ought not to strive directly at the *replacement* of student conceptions – which runs the risk of creating parallel systems of commonsense conceptions and superficial, inert, scientific knowledge – but restructuring of them. This can be done by building up knowledge in a way that it is “anchored” to preconceptions (Clement et al., 1989), or by providing “ontology training” (Slotta & Chi, 2006) to make salient the features to be differentiated and the inferential licences that are associated (and, crucially, that are *not*).

A third implication is that we should find concepts that need to be differentiated in order to be acquired generally difficult for students to master, and certainly not expect the appropriate differentiations to be abstracted spontaneously from everyday experience or just clear and ambiguous presentation of material. It necessary for students to realize that not all - in fact very few - of the connotations associated with commonsense terms (or similar terms in related theories) carry over. Luckily, most students pick this up themselves - which is not to say that explicit practice and guidance is not called for, especially for the more difficult to learn concept.

In this regard, the present hypothesis would predict the “accessibility” of the abstracted elements to affect learnability. This can be understood roughly as how far removed from experience, in terms of the process of abstraction, the concepts are. For example, it would make sense that the concept of chromatic color should be relatively easier to differentiate than innateness (should an unambiguous formal concept of innateness exist), because the abstracted features - hue, saturation, and brightness, that different color concepts into the chromatic color space - find interpretation in intuitive experience relatively straightforwardly. The definition of innateness, on the other hand, as “information acquired by mechanisms other than learning” refers to unobservable properties and depends on *other* differentiated concepts – viz. “information” and “learning” - for interpretation). Instruction should be designed so that students can work their way from common sense, bootstrapped by differentiated conceptions of theories of nearby disciplines on both sides.

Finally, when it comes to discipline-based research into conceptual change in cognitive science students, on the present suggestion the natural starting point is the differentiated (or not) nature of student conceptions. Especially, but not exclusively concerning concepts such as innateness, learning, or modularity, spanning multiple disciplines.

Conclusion

I have presented an outline for a framework for discipline-based research on intellectual development and conceptual change in acquisition of cognitive science concepts.

The proposal is that what gives scientific knowledge its abstract character is that you are not allowed to read into a concept all the features or attributes which intuitively “go together” (connotation), and that you are not allowed to make inferences beyond those that are licenced by formal definitions and the logical structure of a theory. This kind of knowledge is a product of differentiation by abstraction, where some few features belonging to the connotation of a commonsense concept are abstracted away from it, and used as the core of a new, scientific, conceptual framework. In this framework, merely connoted inferential licence does not apply. You can only infer what is explicitly licenced by the theory. This is in contrast to untutored common sense where connotational licence governs (reducing in the limiting case to undisciplined free association and rhetoric conclusion-drawing cued by key terms and phrases in the truly naïve subject).

This concept of differentiation by abstraction draws on discipline-based and cognitive science research into conceptual development in physics students. To what extent does research on learning physics carry over to cognitive science? If the logical structure of theories (in cognitive science there is less reduction to first principles) or the modes of explanation applied (cognitive science employs teleological and rational explanation not recognized in physics) of physical and cognitive theories differ, one would expect to find differences in learning as well. Also, the multidisciplinary nature of cognitive science means that there is less global coherence and more equivocal use of terminology among theories and definitions than in physics, creating unique challenges for the learner. Thus the transfer of physics education theories and approaches would not expected to be entirely smooth.

Another critical point to consider is the domain of application of the differentiation of concepts concept. I would expect it to best characterize the initial state of undergradutate training (with its characteristic confusion and disorientation), and be less applicable to (or less explanatory with respect to) acquisition of higher levels of expertise. In other words, ability to differentiate by abstraction in intermediate between conceptual change in childhood (acquisition of commonsense picture of the world) and high-level expertise in a field. I.e. the first major hurdle in university education.

Some implications for teaching and research were presented. In discipline-based research the application of general principles is very much dependent on the specific content to be studied. Therefore, the same kinds of paradigmatic "test cases" where reproducible and robust differences in student conceptions, patterns of inference, judgments of similarity etc. can be diagnosed, as are found in physics education literature, are called for. (These remain to be worked out more fully, at this stage, and I hope to present preliminary analyses and student data at the conference).

Cumulative work on devising and refining such diagnostic testy cases will enable contrasting interpretations (e.g. differentiation vs. category shift based explanations) to be evaluated and developed further. From a practical standpoint, such diagnostic tools can be used for the purpose of student assessment and gauging the effectiveness of teaching.

Overall, such research should contribute to both our theoretical understanding of learning in general and in our students in particular, which should also be reflected in the quality of teaching and thereby the outcome of learning.

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