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# SELF-ORGANIZATION IN CONCEPTUAL GROWTH

## Practical Implications

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In the famous debate between Chomsky and Piaget (Piatelli-Palmarini, 1980), which included a number of other leading philosophers and scientists, the problem of explaining conceptual growth and change proved so intractable that Fodor was led to declare:

> There literally isn't such a thing as the notion of learning a conceptual system richer than the one that one already has; we simply have no idea of what it would be like to get from a conceptually impoverished to a conceptually richer system by anything like a process of learning.
>
> (Fodor, 1980, p. 149)

During the next decade, however, with the increasing presence of complex systems models, conceptual growth came to be seen as one more example of self-organizing processes by which complex structures emerge from interactions among less complex ones – a process that is evident at all levels from the molecular (Kauffman, 1993) to the cultural (Dennett, 1995). Much remains to be explained about conceptual growth, but it may be said that conceptual growth has been domesticated; it has become part of a large class of phenomena amenable to explanation in terms of concepts drawn from what is broadly referred to as complexity science (Kauffman, 1995).

The self-organizing character of conceptual growth appears to be well recognized by researchers, as indicated by frequent references to it in the first edition of this *Handbook* (Vosniadou, 2008). Nevertheless, its role in both theoretical and applied work has been marginal. Complex systems theory is essentially neutral with regard to theoretical controversies in the field because, according to Brown and Hammer (2008, p. 137), it "describes the full spectrum of phenomena in the literature on conceptual change." It does not help resolve differences between "frameworks" and "knowledge in pieces" views, because both imply emergence of complex structures from diverse knowledge elements (diSessa, 2008, p. 52; Vosniadou, Vamvakoussi, & Skopeliti, 2008, p. 23). Neither is it very helpful in distinguishing spontaneous from instruction-based change (Inagaki & Hatano, 2008). Spontaneous conceptual change more easily fits into a classical dynamic systems template, but this does not mean that instruction and intentional learning lie outside the systemic processes that constitute conceptual change. The relatively neglected challenge for conceptual change theory is producing a dynamic system model in which intentions and instructional interventions are part of the process.

That complexity science should have more impact on theory than on practice is not surprising. But what effect on educational practice should it have? We omit from consideration here complexity science as subject matter in its own right and "systems thinking" as a skill objective. These are vital and challenging constituents of present-day scientific literacy (Hmelo-Silver & Azevedo, 2006; Jacobson & Wilensky, 2006), but they belong on a different ontological branch from the question of what insights drawn from complexity science may contribute to the general promotion and guidance of conceptual growth. That is the question pursued in this chapter. To clear the table for this inquiry, we may categorically reject popular notions that complexity science directly implies the superiority of "constructivist" over "instructivist" approaches. All learning involves self-organization, whether it is learning at the neuromuscular level of weight training or at the advanced cognitive level of creative problem solving. If a student slavishly taking notes during a lecture is learning something, that learning is the result of self-organizing processes in the student's brain and not of knowledge being somehow transmitted from the brain of the lecturer to the brain of the student. But such statements merely dress up well-known truths. Complexity science offers promise of going beyond this to inform educational practice under three conditions:

1. when learning goes awry or stops short of objectives, as in the persistence of naïve concepts despite instruction
2. when the desire is to go beyond the standard expectations enshrined in educational standards, achieving new levels and breadths of understanding
3. when the concern is to accommodate education to emerging societal needs for knowledge creation and innovation.

Applied research on conceptual change has dealt mainly with the first of these conditions. Through several decades of work on knowledge building in education (Scardamalia & Bereiter, 2006), however, we have been more concerned with the second and the third – with extending the range of the possible in education beyond normal expectations and with socializing students into what the OECD in numerous publications is calling an "innovation-driven society" (Organisation for Economic Co-operation and Development, 2010). "Deep understanding" and "expertise" are common terms that refer to learning that goes beyond normal expectations. Within the context of primary to tertiary education there is always a deeper level of understanding that could be pursued, and expertise is something that not only can keep growing but needs to keep growing if one is to remain an expert in a progressive field (Bereiter & Scardamalia, 1993). A conventional approach to accommodating education to the needs of an innovation-driven society takes the form of specifying cognitive skill objectives and incorporating these into curriculum standards (Johnson, 2009). The alternative pursued in knowledge-building pedagogy consists essentially of learning to innovate by innovating – a well-recognized approach in engineering and design education but one that represents a radical departure in education for understanding (Bereiter & Scardamalia, 2006, 2010).

In this chapter we first describe a complex systems model that we believe to have most practical potential in education – a model in which facts, hypotheses, intentions, feelings, and instructional inputs act as constraints on the settling of a connectionist network representing ideas. We then characterize expert learners as skillful managers of this self-organizing process, who treat learning as problem solving and are able to apply problem-solving heuristics and intuitions to it. But conceptual learning, as everyone recognizes, is a social as well as an internal cognitive process. Accordingly, we briefly consider what is involved in a classroom or a school's becoming a community organized around the pursuit of understanding.

## CONCEPT ACQUISITION AS THE SETTLING OF A CONNECTIONIST NETWORK

Newly acquired concepts are emergents, arising from a self-organizing process that at a micro level (but a level still above that of brain processes) consists of ideational interactions that are uncontrollable and unknowable. And these are not the insignificant variations that all behavior exhibits (you never pick up a teacup in exactly the same way twice); they are the very essence of semantic interactions from which emerges a new organization of some part of the conceptualized world. That is the irreducible complexity of conceptual growth, when viewed from a dynamic systems perspective.

Complexity science embraces a number of models and ways of representing the activity of dynamic systems. These can range from realistic simulations, such as one where ants are depicted scurrying around on the computer screen in search of food (Resnick, 1994), to a variety of equation-based and graph-based models. We have found that for thinking about educational processes the most useful type of representation is a connectionist network in which all or some of the nodes are assigned identities as people, ideas, facts, or other meaningful entities (Bereiter, 1991). This is an approach that has proved strikingly productive in the research headed by Thagard (2000, 2006) on explanatory coherence, enabling him to model significant real events such as scientific and medical advances and the outcomes of jury trials. Such "local networks," as they are called, are to be distinguished from "distributed networks" that simulate activity at the neuronal level and typically do not have identifiable nodes except at the input and output ends; while these can do important theoretical work their relevance to conceptual growth is more distant.

As applied to concepts, local connectionist networks model the constraints that exist among propositions. These may be positive constraints such as agreement, entailment, and evidential support, or negative constraints such as contradiction and competition. These are represented by excitatory or inhibitory links between nodes representing propositions. The activation level of any particular node is determined by the sum of the positive and negative activations it receives. This activation level determines the strength of the activations it sends out, thus affecting the activation levels of the nodes to which it is connected. The network "settles" or becomes stable if and when the activation and inhibition impulses coming to each node match the existing activation level of the node, so that there is no further change. (A simplified explanation of this process, using a concrete analogy, is provided in Bereiter, 1991.) The result will be that some nodes have higher levels of activation than others and so are included in the net forming the concept at issue and some have levels that fall below some minimum and so are excluded from the concept. Except in the simplest cases, the results could not be inferred from examination of the propositions involved. Instead, the resulting concept net is an emergent of the interactions involved in the process of satisfying the positive and negative constraints and the eventual settling of the network. In Thagard's model, certain propositions identified as facts receive continuing activation from a central source, so that they are not so readily eliminated as other propositions. However, we have seen an instance of children playing with a network representing theories of dinosaur extinction, adding invented propositions until the network finally rejected the proposition that the dinosaurs are extinct.

Connectionist networks can learn through corrective feedback coming from outside the network. That is how they can learn, for instance, to distinguish male from female faces on the basis of features extracted from photographs. The system settles on one of two outputs: male or female. If it is correct, the positive and negative links of the settled network are strengthened. If it is wrong they are weakened. Gradually judgments improve. But networks can also demonstrate a kind of learning that takes place without external feedback, and this is especially interesting from the standpoint of conceptual change. Such "unsupervised" learning works on the basis of correlation rather than error correction. It can be quite effective in extracting patterns from stimuli and thus is relevant to language and concept learning (Elman et al., 1996). The change in children's explanations of dinosaur extinction referred to earlier is an example of learning without correction. The network of facts and propositions constructed by the children at first settled on a pattern corresponding to the hypothesis that volcanic eruptions and fire killed off the dinosaurs. When the students were questioned as to whether any relevant facts had been neglected, they recalled the layer of iridium found around the world. When this fact was added, the network – an implementation of Thagard's ECHO program (1989) – settled on the familiar asteroid explanation of dinosaur extinction.

## HORTICULTURE AS A WEAK METAPHOR FOR SELF-ORGANIZED LEARNING

Well before complexity science came on the scene, progressive educators used a metaphor that carries a strong flavor of self-organization. It is the horticultural metaphor, which likens the teacher to a gardener and the student to a plant. It is usually contrasted with the familiar factory metaphor. The idea behind the horticultural metaphor is that teaching is a matter of assisting natural growth, which is internally regulated. You can no more manufacture learning, this metaphor suggests, than you can manufacture a cantaloupe. All you can do is provide conditions and nurturance that will support optimal development of the child or the cantaloupe, as the case may be. The horticultural metaphor is in harmony with the idea of self-organization, for the progression from seed to flower to fruit is indeed a process of self-organization, and the gardener's capacity to influence the process is severely limited. The metaphor has serious weaknesses, however. It does not accord well with two facts: first, that the main reason for having formal education in the first place is to teach things that do not come naturally – that are neither preprogrammed in the genes nor acquired through everyday experience; second, that systematic instruction, carried out as if the factory metaphor were valid, is often successful. A satisfactory model of teaching as a self-organizing process must somehow accommodate these two facts.

These strictures apply both to academic skills and to disciplinary concepts, but in this chapter we will deal only with the latter. The idea that the tilt of the earth relative to its plane with the sun determines the seasons is obviously not an idea acquired naturally through experience, and research has shown that even for people who have been exposed to modern cosmology the idea often loses out in competition with the more "natural" idea that warmth varies with closeness to the source of heat (Schoon, 1995). If taught through textbook, lecture, and demonstration, the accepted scientific explanation of seasonal change will take hold with some students, even though it fails with many others. In cases like this, where a large percentage of students fail to grasp the intended concept, it seems as if self-organization in the form of cognition settling on whatever comes most naturally is the enemy of conceptual growth. Both the horticultural metaphor and the factory metaphor fail. The education system labors to bring forth a cantaloupe, but a potato emerges instead.

## BEYOND GARDENING: ON TRYING TO BECOME A CANTALOUPE

George Bernard Shaw, in his preface to *Back to Methuselah*, criticized an experiment that was supposed to demonstrate that acquired characteristics cannot be inherited. The scientist cut off the tails of mice in successive generations and found that mice continued to be born with long tails. Nonsense, said Shaw. For the experiment to prove anything, the mice would have to *want* to have short tails, just as the ancestors of today's giraffes must have wanted to have longer necks. While Shaw's quirky notion of purposeful evolution finds no support in biology, there is plenty of evidence that in conceptual growth, which is also an evolutionary process, intentions make a difference.

The most straightforward way of incorporating intentions, goals, motives, and the like into a connectionist model is to treat them as constraints. They are not hard constraints like natural laws – they can be overridden or ignored – but they can function somewhat like laws. Thagard has incorporated emotional predispositions and other personal reactions into his coherence model as constraints (2006). They play an important part in modeling decision processes that do not accord well with strict rationality, such as jury decisions that are swayed by feelings about the defendant or the accusers (Thagard, 2003). In classroom work we have introduced official standards as information for students – what the Ministry of Education expects them to learn from the unit they are working on – but understandably those are not mere items of information; they carry an authoritative weight that would not be shared by, for instance, some unknown expert's opinion about what should be learned. And yet, like a factual scientific statement, they can be overridden by a decision mechanism that tries to maximally satisfy all the relevant constraints.

The concept of constraint, as used in information and design sciences, would be a useful one for teachers to have in their repertoires. Unlike the related concept of restraint, it has a positive connotation. It is what enables constructive processes to progress, to move toward consolidation of a design or a concept. Indeed, Perkins (1991) has explained creative work as the successive addition of constraints. Thinkers need to realize that they are continually adding constraints and to consider always whether the constraint is valid and useful or whether it is lopping off branches containing alternatives that should not be prematurely eliminated. The old concept of functional fixedness (Duncker, 1945) can be understood not as a personal defect but as the adoption of deleterious constraints. Similarly, conceptual growth can be limited by unfortunate constraints, such as requiring natural phenomena to have a purpose relevant to human welfare or to a cosmic plan. Such constraints effectively put evolution beyond comprehension, but they also affect more mundane understandings, such as that of the child who opined that there is less gravity on the moon than on the earth because there aren't as many things there that need to be held down.

## THE EXPERT LEARNER AS A MANAGER OF CONCEPTUAL SELF-ORGANIZATION

In a study of young children's word learning, Carey and Bartlett (1978) casually introduced a new color name into preschool activities. The new word was "chromium," and it referred to the color olive-green. (They did not use the word "olive" because it would provide a cue for those children familiar with the fruit.) The teacher would say things like "Hand me the chromium block. No, not the red block, the chromium one." In what Carey and Bartlett called "fast mapping," the children quickly caught on to the idea that "chromium" was a color, but it took some time for them to work out what that color was. According to Carey (1978), connecting the word with the intended color involved more than just linking the word to a percept; it involved reorganizing the semantic space of color concepts so as to make a place for the new concept within a network of related concepts. In contemporary terms, it involved conceptual self-organization. This idea of word learning as involving reorganization of a sometimes vast network of concepts was made explicit and implemented in latent semantic analysis (LSA), which locates concepts in a Euclidean space of hundreds of dimensions (Landauer & Dumais, 1997). Using LSA to model normal vocabulary growth, Landauer and Dumais inferred that a sizable proportion of new words (two out of the average seven words per day learned during childhood) entered a child's vocabulary not when the word was being actively processed but at some other time when spontaneous processes of semantic organization made it settle into a position relative to other words. Vocabulary growth according to this model is an eminently self-organizing process; and the model applies to a large body of findings that have followed upon Carey and Bartlett's original study (Swingley, 2010).

There is more to the "chromium" story. The preschoolers studied by Carey and Bartlett were not very successful in nailing down the new color concept. However, according to Carey (1978), the children exhibited two different strategies. In one, which we call *direct assimilation* (in acknowledgement of the process identified by Piaget), the children immediately equated chromium with green, and then gradually learned to discriminate between them. Others adopted what Carey called the "odd color, odd name" strategy. In effect, they set up a *placeholder* for the new concept (cf. Bereiter, 2010; Gelman & Brandone, 2010) and gradually attached information to it. These children made faster progress than those adopting the direct assimilation strategy. In either case acquisition of the new concept was a self-organizing process, but learning was more intentional, more under the learner's control in the case of those adopting the "odd color, odd name" strategy. They exhibited more learning expertise.

Expert learners are people unusually adept at acquiring new skills and understandings. As with most kinds of expertise, the natural contrast group is young children, who serve as all-purpose novices. (That young children may be more adept than adults when it comes to foreign language learning does not constitute a counter-example. Hard-wired excellence does not count as expertise; we do not call fish expert swimmers.) Of particular interest from the standpoint of conceptual growth is how people respond to concept-altering information.

Although differences in approaches to learning show up even with such simple tasks as learning a new color term or learning a single new concept in an already familiar domain, the difference between expert and nonexpert learning becomes much more striking when some advance in the complexity of knowledge is involved. To about 100 children ranging from first through sixth grade, Chan, Burtis, Scardamalia , and Bereiter (1992) presented a series of statements about germs or dinosaurs and asked children to think aloud after each statement. One of the text statements that proved most provocative of differences in response was the following:

> Harmful germs are not trying to be bad when they settle down in your body. They just want to live quietly, eat, and make more germs.

Responses were scaled according to five levels. The first two levels were ones at which the child did not show evidence of having assimilated the new information at all but instead responded to an isolated word or proposition by recalling old information that was cued by it. At Level 3, however, one might get a comment or paraphrase that makes it clear the passage had been taken in. For instance:

> That means they don't want to really hurt you, but they just want to live quietly and eat the food you digest and all the things that could go in your stomach and they just want to get more bacteria.

Yet at Level 3 the child shows no recognition that the statement contradicts the popular concept of germs as aggressors. At Level 4 such disparities are recognized and at Level 5 the child makes an effort to reconcile or deal with them – for instance, by considering that germs have no intelligence and thus have no idea of the effects of their actions. Level of response was positively correlated with amount learned from the texts. So were age and prior knowledge, as could be expected. However, statistical path analysis indicated that learning expertise, as indicated by response level, exerted the only significant direct effect on learning, and mediated the effects of age and prior knowledge.

In case studies of college-level students in music and medicine, expert and nonexpert learners were identified by asking instructors to pick out successful but typical students on one hand and on the other hand students whose approach to their subject resembled that of experts. Given a novel learning task in their field, the nonexpert learners manifested the *direct assimilation* approach discussed previously. Ghent (1989) presented a novel piece of piano music – a transcription of Indonesian wayang music – to a concert pianist and two piano students. In thinking-aloud protocols, one student dealt with the novel challenge by considering what the piece resembled most closely in music he was already familiar with. His answer was French Impressionism, and he proceeded immediately to play the piece in the manner of Debussy: a clear case of direct assimilation *à la* Piaget, fitting the novel into an existing schema. However, both the concert pianist and the student identified as expertlike focused on what was problematic in the new piece and worked on how to solve the problem (i.e., how to produce on the piano the percussive effect of music originally played on drums). Thus we may term their approach *learning as problem solving.* This same distinction between *direct assimilation* and *learning as problem solving* appeared in research by Tal (1992), which followed typical and expertlike medical students through a variety of tasks that arose in the regular course of their clinical training.

Problem solving is a self-organizing process almost by definition. It is goal-directed activity in which the path to the goal is not known in advance but must be discovered (Newell, 1980). If a routine procedure achieves the goal, then it is not problem solving. Most human learning and, as far as we know, all learning by non-human creatures is unproblematic – that is, it goes on without applying problem solving skills or resources to the task of learning itself. (The learning may arise from problem solving, but that is a different matter; we are talking about learners treating learning itself as a problem. This is a distinction between learning *through* problem solving and learning *as* problem solving (Bereiter & Scardamalia, 1989).) There are important kinds of human learning, however, that are problematic and do not take place or do not take place efficiently without problem solving. In a study of reading comprehension strategies, using thinking-aloud techniques, Bird (Bereiter & Bird, 1985) found that one strategy used by skilled adult readers when they encountered a difficulty in text comprehension was to formulate the difficulty as a problem and then try to solve it. They also used more routine and familiar strategies such as backtracking and paraphrase. An instructional experiment intended to teach the expert strategies to school students produced significant gains in reading comprehension and there was evidence that students actually used the taught strategies – except for the problematization strategy.

In a related line of research, we asked elementary school students to imagine they were allowed an hour a day to learn anything they wished. When questioned about how they would go about their chosen learning, students generally showed a good sense of what resources and methods they would use. However, they treated learning as a straightforward process of applying routine procedures, they had little sense of how long the learning would take, they anticipated no difficulties, and when asked what they would do if they did encounter difficulties, they suggested nothing more than persistence in the routines of reading, practice, and so forth. This was in contrast to adults who, when posed the same hypothetical situation, had a more realistic sense of the amount of work and difficulty that lay ahead. In short, they saw achieving a learning objective as a problem to be solved.

An educated adult, undertaking learning in an unfamiliar field, nevertheless brings a useful body of knowledge to the task. It is knowledge about learning. Based on prior experience, the adult will know, for instance, that:

- There is probably more to be learned than they imagine at the outset.
- They may often be unable to tell what is important from what isn't, and so had better err on the side of assuming things are important.
- Words that they think they already know may turn out to have different meanings in the new discipline.
- Their initial understanding is likely to be simplistic, and so they had better be on the watch for complicating factors.

- No matter how unappealing the field might seem to them, there are intelligent people who find it fascinating, and so they should be on the watch for what it is that arouses the intellectual passions of people in the new discipline.

Naïve students, however, lacking generic knowledge about learning, will do things such as the following:

- Give no thought to how much more there is to learn, and jump to conclusions on the basis of the little they have already learned.
- Judge importance on the basis of superficial cues; e.g., assume lists are important, especially if they are numbered.
- Make subjective judgments of importance, ignoring events or statements that do not stand out as important in their own right – what Brown, Day, and Jones (1980) called the "copy–delete" strategy.
- Assume words mean what they are used to having them mean.
- Quickly construct simplistic interpretations, which are then retained in the face of contraindications.
- Dismiss whole topics as boring, without attempting to discover what might be interesting in them, while allowing themselves to be captivated by items of tangential interest.

In connectionist terms, these predispositions function as constraints that cause the process of conceptual self-organization to settle prematurely on simplistic and often incoherent concepts. Knowledge about learning of the kinds attributed to educated adults can also serve as constraints on the learning of new concepts, but these are constraints that prevent the process from premature settling and that boost the search for alternative and more complex meanings.

Of course, merely possessing declarative knowledge about learning does not guarantee that it will function to constrain concept learning. Like other relevant factual knowledge it needs continual boosting to keep it from being nullified or simply ignored. Expertise in learning means having an overarching system that ensures a privileged status for facts, both facts pertaining to the concept in question and what may be called *metacognitive facts* – facts that pertain to the learning situation as a problem space. But the boosting, which may be imagined as a continual input of energy, has to come from somewhere. For mature experts, the boosting may come from firmly established habits of mind, which influence cognition in a wide range of situations. In the classroom, boosting may come from the teacher's continual issuing of reminders about things that need to be taken into account. Not to be neglected, however, is the peer or classroom culture, which can strengthen certain constraints, weaken others, and in more general terms constitute an overarching system that can strongly influence for good or ill the self-organizing processes by which concepts develop.

## CLASSROOM CULTURE ORGANIZED AROUND PURSUIT OF UNDERSTANDING

Eichinger, Anderson, Palincsar, and David (1991) analyzed an argument among a small group of Grade 6 students about whether, on a rocket trip to Mars, water should be carried in the form of a solid, liquid, or gas. The question was assigned by the teacher, with strictures that the group must reach a decision and must give reasons for their answer. After some initial discussion, a majority of the students were prepared to vote for gas, on grounds that it is lighter. However, the students took seriously the norm, emphasized throughout the trip to Mars unit, which required that students have reasons for their opinions. As a result, one student's pro-gas position was discounted because he admitted to having no reason for it. Then another pro-gas student, who was particularly attentive to the reasons given by other students, shifted to being in favor of liquid water, which then became the group's choice. The transcript of the argument makes it obvious that these were children and not model miniature adults. They turned the scientific problem into a win–lose contest, tried to score points by ridicule, and generally did not appear to take the problem very seriously. And yet the norm requiring reasons for opinions survived and ultimately led them to a scientifically reasonable conclusion that differed from where most of them had started.

The "you must have a reason" norm was part of a sustained effort by the teacher to establish a classroom culture disposed toward scientific thinking. Success in such an effort is only achieved to the extent that students themselves uphold the norms, bringing them into play without reminding by the teacher. Once this state is achieved, the boosting of norms as constraints becomes part of the normal round of classroom life and is self-maintaining.

The "you must have a reason" norm and the related norm of paying attention to both positive and negative evidence are essential to any rational controversy. A dramatic example of what can happen when such norms are absent or allowed to lapse comes from the notorious controversy in the United States about Barack Obama's place of birth. The claim that he was not actually born in the United States and therefore not a legitimate president persisted despite evidence from a legally acceptable birth certificate and newspaper announcements of his birth in the state of Hawaii. "Birthers," as the conspiracy theorists are called, questioned this evidence, demanding to see a more detailed form of birth certificate, which was eventually provided. President Obama criticized the mass media for keeping such a silly controversy alive. However, one fact that was seldom brought up and that figured hardly at all in the claims and counter-claims raging through the media is one that points to almost universal failure of the "you must have a reason" norm. The birthers offered no plausible reason for believing that Obama was not born in the United States (except for a Kenya birth certificate that was immediately revealed as a crude forgery), nor did media pundits demand a reason. As a result, the whole controversy has been carried out at a level of rationality below that of the sixth-graders we have been discussing.

A rising emphasis on argumentation (e.g., Andriessen, Baker, & Suthers, 2003) promotes classroom cultural norms that give an important place to empirical evidence, logical reasons, and openness to different viewpoints. These are norms relevant to evaluating explanations, but they do not deal with how explanations are actually produced or grasped. Consequently, their contribution to conceptual growth is limited. In terms of a distinction we have elaborated elsewhere (Bereiter & Scardamalia, 2003, 2006), they are cultural norms mainly applicable to activity in "belief mode" rather than "design mode."

What kinds of classroom cultural norms would act as favorable constraints on academic activity in design mode? Norms pertaining to the pursuit of understanding would surely rank high by any modern standard. Relevant norms would include "seek out big ideas," a norm of treating all ideas as potentially improvable, and another that figures in Scardamalia's (2002) set of 12 knowledge-building principles, "rise above." "Rise above," in the context of concept development, is synonymous with the more formal term, "synthesize." When you encounter conflicting ideas, try to create a third idea that coherently combines the strengths of the conflicting ideas. Promoting classroom cultural norms often entails concept teaching in its own right – teaching the distinction between opinions and evidence, developing the concepts of big ideas, synthesis, and what constitutes an improvement in explanatory ideas.

Cultural norms, when fully internalized, serve to shape not only classroom behavior and group cognition but personal identity as well. Young students seem readily to identify themselves as researchers or junior scientists. But such self-identification sometimes rests on a very meager set of norms. To make a difference in conceptual development, classroom norms need to have some bite – to strengthen what needs strengthening and to suppress what needs suppression.

## FUN WITH IDEAS

Earlier we mentioned students playing around with propositions about dinosaur extinction until finally the software application they were using settled on the conclusion that dinosaurs were not extinct. The students were having fun, but the technology they were using was not a game or some kind of "edutainment." It was serious "thoughtware" – a version of Thagard's ECHO (1989), designed to assess coherence in a set of explanatory propositions and facts. What the students discovered was that the program could also be used for imaginative play with ideas. Young students can find a way to turn almost any activity into a game – sometimes to the detriment of educational objectives, as when they turn what should be a serious assignment into a competition to see who can finish first. Although often it is desirable to block such diversions, we want at this point to consider possibilities of turning playfulness to good account.

Of course, the value of play with ideas is already well recognized in conventional educational wisdom, with Albert Einstein almost invariably cited as the exemplar and chief proponent. It allows self-organization at the idea level to go on with relaxed constraints, which may result in the emergence of new conceptual combinations leading to conceptual growth. Not all intellectual play is play with ideas, however. Word puzzles, logical and mathematical puzzles, and games of strategy such as chess and go may have cognitive benefits of some sort, but they do not generally involve concept development except for concepts internal to the game or puzzle type.

Play with ideas can take two distinct forms. In one form certain concepts themselves serve as constraints on a game-like system, so that achieving goals within the system requires accommodation to these constraints and thence, under favorable conditions, to actually learning the concepts. Simulation software has this character, which is manifested clearly in the ThinkerTools Force and Motion software (White & Frederiksen, 2000). The simulation environment operates according to Newtonian laws of motion. Challenges are presented calling for the application of forces to get a screen object to behave in a particular way, such as hitting or stopping at a designated target. However, the software provides enough flexibility that students can devise games of their own and can alter properties and physical laws to investigate the results.

The other form of play with ideas is closer to the Einstein model, featuring playful explanation. We once recorded a group of Grade 5/6 students discussing the idea that the earth is a globe. They quickly deduced that this meant people in Australia were upside down, and they found this quite amusing. Ideas flew thick and fast – that the earth was really a disk, not a globe; that people in the southern hemisphere were on the inside of the globe, not the outside; and so on over various of the naïve theories reviewed by Brewer (2008) and Vosniadou, Vamvakoussi, and Skopeliti (2008). However, one member of the group who seemed to be better informed on cosmology asserted that gravity drew things toward the center of the earth and that therefore people in the southern hemisphere were not upside down and that things dropped there fell to earth the same as they did in the northern hemisphere. He was ignored. He repeated his statements only to have them summarily dismissed. Our interpretation is that the others rejected him because he was spoiling their fun.

One invented theory that received an enthusiastic response in the group was that the earth is like a Ferris wheel, so that as it rotates the people on board remain upright. It must not be supposed that the children took this theory seriously. Although no one criticized it, its inconsistency with everyday experience is too glaring to have been overlooked. What the Ferris wheel theory illustrates is a very loose form of model-based explanation (Clement, 2008; Nersessian, 2008). The students were playing at explanatory model creation in much the way that a kitten plays at catching mice. Although direct evidence of its benefits are lacking, one is entitled to suppose that such play must have a significant and perhaps an essential role in conceptual development.

## TECHNOLOGY TO SUPPORT CONCEPTUAL SELF-ORGANIZATION

Much of recent learning technology is relevant to conceptual change. This includes simulations and microworlds that enable students to explore and test ideas, as well as tools directly applicable to building conceptual models (e.g., Wilensky & Reisman, 2006). Of particular importance for collaborative concept development, however, is technology to support the kind of dialogue that transmutes information into public knowledge – that is, knowledge-building dialogue. Here the pickings are more limited. Besides the ubiquitous “threaded discourse,” which generally provides no process support whatever (Hewitt, 2005), the discursive side of conceptual work in education is dominated by argumentation software (Andriessen et al., 2003). As we have noted previously, argumentation can play a significant role in concept development, but it is not the process through which conceptual advances are made. It represents the critical rather than the creative aspect of concept work. Technology to support the production and improvement of explanations rather than only their evaluation ranges from highly structured and content-laden applications such as ExplanationConstructor (Sandoval & Reiser, 2004) to open software environments, such as Knowledge Forum (Scardamalia & Bereiter, 2006), where content is brought in by the learners and knowledge-building dialogue is facilitated by affordances for linking, organizing, labeling, visualizing, and evaluating dialogue contributions.

A number of design criteria emerge for technology to support concept-developing dialogue, regardless of the extent to which the technology is content-specific versus content-independent and scripted versus structured by the users:

- The overall design of the technology should be oriented toward support of explanation through collaborative theory and model building (with such other kinds of dialogic activity as argumentation, planning, and knowledge sharing serving auxiliary purposes).
- It should be possible to connect various modes of communication (face-to-face, videoconferencing, asynchronous and synchronous discussion, text messaging, etc.) in support of a *single* coherent dialogue – coherent not merely in having a shared topic but in having followable lines of thought running through the various modes of expression and communication.
- It should be easy to build models, use multimedia to explore ideas, and bring the results of experiments, simulations, web searches, and so on into the main line of the knowledge-building dialogue.
- It should be possible to link any idea (however it might be represented) with any other ideas, for purposes of comment or synthesis.
- Without disrupting the main line of a dialogue, it should be possible to carry on a meta-dialogue, which is dialogue about the main dialogue – about its content, progress, difficulties, and so on.
- Contributions to dialogue should be tagged not only as to topic but also according to what may be broadly categorized as speech acts. Automatic tagging, using semantic analysis, could be combined with tagging by users so as to combine the strengths of both and to maximize the educational benefit from use of semantic tags.

We are not aware of any existing technology that meets these criteria. Knowledge Forum, which was designed to support knowledge-building discussion, perhaps comes closest (Scardamalia & Bereiter, 2006); but it does not fully meet any of the criteria. We are at present organizing an open source community effort to build a next-generation environment that will meet these along with more advanced design criteria.

## CONCLUSION: COMPLEX SYSTEM ACCOUNTS OF CONCEPTUAL CHANGE MAY BE TRUE, BUT WHAT GOOD ARE THEY?

Complex system models of conceptual change are mathematical models, even if the mathematics is not the kind learning scientists are accustomed to. Like many other mathematical models, they may have considerable power in accounting for data, but they lack both the insight-bringing quality and the practical suggestiveness of qualitative explanations that take a narrative or "how it works" form. It seems likely that research on conceptual change will continue to deal mainly in "how it works" explanations, not unlike the descriptions we employ in everything from explaining noises in our building's plumbing to explaining why educated conservatives deny climate change. In this chapter, however, we have tried to indicate some ways that viewing conceptual change in terms of self-organizing systems may have educational benefit. These require treating the teacher or the autonomous learner as manager of a self-organizing knowledge-creating process, much like the manager of a creative design team. The manager does not control the process or guide it to a pre-determined outcome. Instead, teaching acts, intentional acts on the part of the student, and information from authoritatitve sources function as inputs to a self-organizing system, with results that are not wholly predictable. We have proposed that these inputs be regarded as non-binding constraints on the settling of a connectionist network, chosen so as to optimize even if they do not predictably determine cognitive outcomes. The outputs of such a process may be thought of as conceptual artifacts (Bereiter, 2002; Paavola & Hakkarainen, 2009): ideal objects that may be represented and worked with in many different ways (Nersessian, 2008). Like other artifacts, such as computer software, these knowledge products carry an implicit version number. They represent something put out for use by a community, while design of the next version proceeds either openly or behind the scenes.

In practical terms, an important advantage of a complex systems approach is that it can assimilate rather than compete with other approaches to promoting conceptual development. Two major approaches to education for concept development are ones that feature evidence-based argumentation (Bell & Linn, 2000) and ones that focus on explanation and explanatory power (Bereiter, 2012; Clement, 2008; Thagard, 2008). It is possible to add explanation building to an evidence-oriented approach (e.g., Matuk, et al., 2012), but arguably this puts the cart before the horse. It should not be necessary to decide between these approaches, both of which have obvious merit. But a synthesis cannot be merely additive. It needs to conceptualize concept development at a higher level, which is the level that Piaget struggled toward in his genetic epistemology (Piaget, 1971) and which currently reaches its fullest realization in complex systems theory.

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