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The Evolution of Umwelt and Communication

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Abstract

Existing educational practices focus on subject matter knowledge that is, through the act of teaching, brought into the heads of students. Materials, texts, or images qua aspects of the learning environment are treated as given in terms of fixed and unambiguous structures (ontologies). Drawing on examples from a large data base on learning physics through laboratory activities, I show that (a) students do not perceive and act in worlds shared with physicists and physics teachers and (b) during collective activities, students evolve new domain ontologies and language games by interacting with each other. Because of structural constraints in the environment (teacher, textbook, equipment), initially quite different ontologies and language games converge; the shared language games often become more commensurable with (existing) scientific ontologies and language games. In this co-evolution of ontology and language game, gestures provide an important bridge between laboratory experiences in science and scientific discourse about abstract entities.

Introduction

“Second order cybernetics says that it is only through the established structural couplings that signs can acquire meaning.” (Brier, 1998, p. 100)

Existing educational practices focus on subject matter knowledge that is, somehow through the act of teaching, brought into the heads of students. Even the staunchest constructivist educators are often astonished that “the evolution of students’ ways of thinking about phenomena tends to be a slow and piecemeal process” and that “students’ informal ideas have been shown to persist through extended tuition in science” (Scott & Driver, 1998, p. 67). Other constructivist educators suggest that students actively resist conceptual change (e.g., Duit & Treagust, 1998, p. 15-17). In their astonishment these educators never question the ontological status of phenomena, activities, and other pedagogic offerings; they take the curriculum materials as unequivocal stimuli perceived in the same ways by any individual (students, teachers) and independent of their experiences. In these researchers’ views, the problem lies with learners’ prior understanding.

Few science educators ask whether there is any agreement between the structures that they think they provide students with and those students actually perceive, act towards, and expect. A small number of studies conducted during the recent past has made evident that students often do not perceive or perceive the material constellations (equipment, materials, sign systems) provided to them in ways that differ (e.g., Roth, 1998; Roth, McRobbie, Lucas, & Boutonné, 1997a). In one Australian study, students were asked to predict what would happen if a person on a rotating table would spin a bicycle wheel which is then moved through different spatial orientations (Roth, McRobbie, Lucas, & Boutonné, 1997b). Students not only predicted (expected) different types of movement (stop, rotation) but also made antagonistic observations (motion, no-motion) and drew on widely differing theoretical descriptions to account for what they had observed.

If we understand the students as complex adaptive systems, it makes little sense to attempt to describe learning trajectories in terms of curricular artifacts, events, and demonstrations whose ontologies and mereologies are uniquely fixed. (On the mereology, the science of parts and wholes see Smith [1997].) Rather, we need to know what it is that the system reacts to and interacts with. That is, we need to know not only that students use different descriptive and theoretical language for a range of given phenomena, but we need to ask what these structural properties (phenomena) are as seen from within the system.

Hand in hand with the disregard for the world expected, perceived, and acted in (and towards) by learners goes a disregard for the role of language and language change. Much of cognitive science and education (and the domains they draw on such as linguistics and psychology) are focused almost exclusively on single speakers or on turn-taking issues at some moment in time. They have largely ignored dynamical issues such as ontogenetic and evolutionary trends in the appropriation of language that is used to bring and talk about abstract concepts. Here, school science laboratories may constitute ideal sites for empirical studies of how humans evolve new ontologies, language games, and gestural expressions.

The purpose of this article is to provide a framework, exemplified by specific cases from an extensive empirical database of learning in physics classrooms. In this framework, organism-environment entities are understood as complex systems that are characterized by their tendencies to achieve global coherence despite the non-linearity of the interactions. Learners are complex dynamic and adaptive systems similar to other complex systems that are a key to understanding the complexity found in nature (Prigogine & Stengers, 1984) and particularly in the learning environments relevant to human forms of life. My framework embodies second-order cybernetics and provides an approach to understanding knowing and learning more appropriate than traditional frameworks for explaining the data I constructed in fine-grained empirical studies.

Second-Order Cybernetic Model of Knowing and Learning

Second-order cybernetic models focus our attention on the learner as organism who has to generate this structure by interacting with the environment (Brier, 1998; Luhmann, 1995; Steels, 1997). Here, organism and environment are understood as purely heuristic ways of dividing an indivisible whole, for organism and environment are structurally coupled so that they cannot be modeled independently of each other (Figure 1). That is, if we use a mathematical (artificial neural network) model, we can no longer uncouple environment from organism by means of a separation of variables (as is done in solving differential equations) because the two supposedly different parts share the same parameters (Wheeler, 1996). The organism always perceives and acts in its “umwelt” (von Uexküll, 1973), the environment as it is apparent to the organism rather than in some abstract given universe. As the organism acts and perceives, the umwelt changes in an evolutionary way. This adds totally new entities to the ontology and differentiates existing entities.

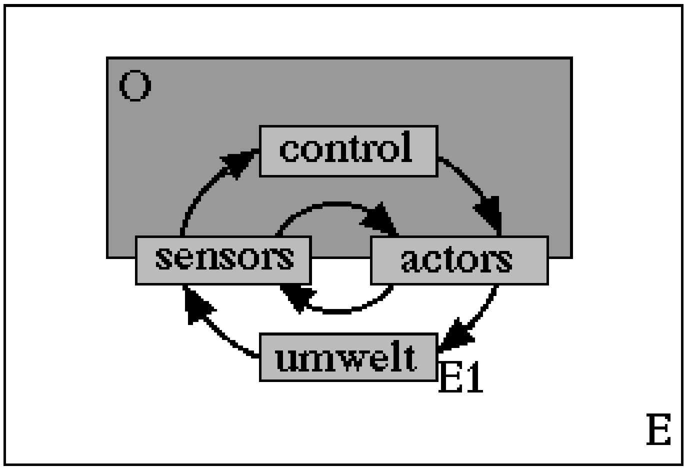


Figure 1. Model of the organism-environment relation. The organism is structurally coupled with the environment. It does not perceive and act in some absolute environment but always in its umwelt.

To bring “umwelt” in a better focus, consider the following cases. Children do not just believe that there is a Santa Claus but talk about and act in a world (umwelt) were Santa is a reality; they write letters, put up boots to be filled by him, stay up to attempt to catch a glimpse of him, and so forth. Similarly, the schizophrenic does not just believe in some dark force, but directs his attention and actions such as not to succumb to it; this force is real to him shaping his behavior. Most organisms (e.g., animals) acting like non-reflectively in the world can be modeled with first-order cybernetics. However, some organisms such as humans act in such a way that they not only engage in their umwelt but also see others and themselves acting as organisms therein; they orient their own actions such that they become accountable to these other organisms. To get this kind of reflexivity that characterizes human cognition, we need a second-order cybernetic model (e.g., Luhmann, 1995).

In this article, learning is viewed in terms of the evolution of common worlds. This presupposes that a minimum of two organisms become attuned in their actions and perceptions to the same objects and develop shared language games (Brier, 1998). Although the two agents may begin with their own umwelt (ontologies have the same or very similar mereologies), they frequently evolve a common language game because they are structurally coupled to the same universe and as part of the same ecological pressures and similar developmental trajectories. Whatever emerges as common to the ontologies involved is symmetrical with respect to the two or more agents and therefore is something like a “universal language” (Brier, 1998). Whenever there is a new agent, or existing agents evolve a new feature in addition to their existing ontologies, there is an opportunity to expand pre-existing linguistic forms.

Thus, “[w]hat information gets preserved and thus what the shape is of a language, is driven by various selectionist criteria, including attempts to maximize the communicative success, minimize cognitive processing and memory load, and be compatible with the limitations of the sensorimotor apparatus” (Steels, 1997, p. 8). Language coherence therefore emerges as part of evolutionary trajectories that couple success-in-use and use. Empirical studies show that words, gestures, and syntactic conventions are preferentially employed when their use leads to local (group) and global (classroom community) success (e.g., Roth & Duit, in press).

When there are at least two agents that learn by exploring the world, they can begin communicating. A fundamental condition for intersubjectivity is that different agents categorize their sensorimotor experience of the world in terms of distinctive features (e.g., whole, parts, and attributes) that are similar, even when distinct feature sets are appropriate. In a seminal program of work, Luc Steels and his associates construct bottom-up models of intelligence by allowing robots who have no repertoire of perceptual distinctions and no lexicon to evolve to the point that they use language to communicate about features in a shared world (Steels & Vogt, 1997). That is, these robots learn to structure the world through experience (action, perception, expectation) and subsequently expand their evolutionary success (survival) when they begin to establish a common language game, which allows them to cooperate and to achieve ecological advantage. Two robots that have built up their own feature sets (ontologies) are then brought together and permitted to build communication from the most rudimentary behavioral primitives. Each robot can learn new words, new features, or modify words by interacting with the other robot. They negotiate a ‘universal language’ (Brier, 1998).

Action, Perception, and Expectation

To learn, an organism has to move or move about. When an organism is prevented from moving, it does not learn which, at the level of the neuron, leads to a stoppage or even stunting of myelination and axon sprouting (Churchland & Sejnowski, 1992). These authors provide as example the experiment in which pairs of kittens were brought into the same environment but one drew the cart into which its partner was tied such that it was restrained from motion other than with the head. Kittens that pulled the carts and therefore had opportunities to physically explore the environment had a significantly higher brain development and cognitive function than their partners fixed into the cart. Movement makes salient variation and invariants in the environment to the perceptual subsystems; without motion, there is no perception because staring at the world (or some part of it) and identifying properties alone does not allow the construction of significance within the organism (Heidegger, 1977; Merleau-Ponty, 1945). In the brain, covariation between action and perception lead to the co-excitation of neurons which, according to Hebb's rule, leads to learning:

> When an axon of a cell A is near enough to excite cell B or repeatedly or persistently takes part in firing it, some growth or metabolic change takes place in both cells such that A's efficiency, as one of the cells firing B, is increased. (Hebb, 1949, p. 62)

Recent cognitive neuroscience research provides strong supportive evidence for the integration of action and perception in the same areas of the brain: Those neuronal groups that are active when an organism moves are also active when the organism recognizes movement (Decety & Grèzes, 1999; Müsseler, Aschersleben, & Prinz, 1996). Furthermore, objects are represented as collections of views—resulting from moving around them—rather than as explicitly related parts or three-dimensional models (Wallis & Bülthoff, 1999).

From a phenomenological perspective, this action-perception relation leads to our experience of the world and things that are first ready-to-hand (available) prior to becoming present-at-hand (available to conscious awareness). In humans, action and perception are associated with expectations so that the relationship between the embodied agent and perceptual field is constitutive and not merely a correlational; otherwise, there would not be a subject with a field articulated in specific ways (Merleau-Ponty, 1945). Acting is a condition of our conscious awareness of the world. New modalities of acting (sometimes brought forth through chance, sometimes through planned variation) lead to new ways of perceiving and expecting: and thus new worlds are brought forth. In this bringing forth of new worlds, language plays a central role. Describing, classifying, theorizing, or aesthetically admiring are all different, non-manipulative forms of interacting with the world. In these interactions, language is centrally involved in affording specific forms of activities (Taylor, 1986).

The co-occurrence of action, perception, and expectation is exploited in sensorimotor theories of cognition which hold that all forms of higher cognition make use of the same structures as sensorimotor activity (Newton, 1996). Recent neuropsychological studies show that brain activity during the production of language involves parts of the brain that are active during motor activity. Language does not have a brain module on its own but appears to make use of neuronal groups that have developed in response to sensorimotor activity (Bates, in press). Language, as all forms of signs, is thought to arise via semiotic extension from sensorimotor ideas. In this emergence, gestures seem to play core role, for they provide a link from manipulation of objects in the world (ergotic, epistemic movements) to iconic and symbolic gestures (symbolic movements) which become signs (Roth, 1999, in press).

Context of Empirical Studies

Over the past decade, I conducted micro-analytic studies of learning in physics classrooms where students had the opportunity to enact investigations, sometimes of their own design, more frequently designed by the teacher. The studies provided the empirical examples in the present article involve students between 16 and 18 years of age (grades 10-12) who attended school in Australia, Canada, or Germany (2 studies). In all countries, students who take physics represent a self-selected sample of average to above average students, for physics is usually regarded as one of the more difficult school subjects.

In all the examples used below, the respective students were asked to explore a given set of materials and circumstances. Teachers expected students to generate observational and theoretical descriptions of the phenomena. It was also clear to the respective teachers that students were probably not all coming to the same results; but they consistently attributed differences to cognitive deficits (“they don’t get it,” “not smart enough to do physics,” etc.). The phenomena included events in a computer-based Newtonian microworld (grade 11, Canada), rotational motion (grade 12, Australia), static electricity (grade 10, Bremen, Germany), and chaos theory (grade 10, Kiel, Germany). (Detailed descriptions of the databases, curricula, and design of each project are available for the studies in Australia [Roth et al., 1997a, 1997b], Canada [Roth, 1995, 1996a], Bremen [Roth & Welzel, 1999], and Kiel [Roth & Duit, in press].)

In all cases, two or three cameras recorded the classroom events over periods of 3 weeks to 5 months leading to a combined database of several hundred hours of tapes. When students work in small groups (3-5), each camera was focused on one group. Groups were selected so that the students in the samples were representative of the population. Over the extended periods of study, groups were selected such that the data reflect both longitudinal developments of individual students (by following the same students over weeks and months) and (by switching with the other camera(s) between groups) more cross-sectional information about learning. The videotapes were transcribed and the verbal transcriptions enhanced by information about gestures, activity, and salient materials.

Learning and Self-Organization in Physics Classrooms

Existing educational practices treat learning as a matter of getting structures existing in the universe (objects, language) into the heads of students. Even those educators who proclaim a commitment to (radical) constructivism teach in ways that are commensurable with such a notion of learning that resembles linear imaging processes. We often hear and read how they set up an experiment or demonstration and, at best, expect students to construct different ideas about the event, which they nevertheless take for given a priori. However, as I have argued for some time (e.g., Roth et al., 1997b), objects and events in some learning environment cannot be assumed to constitute a stable world. Rather, students as learning organism not only have to evolve a language game (or, as some like to express it, "construct an understanding which they negotiate") but they also have to find where to make the relevant cuts in the perceptually-available world. They have to establish their own ontology and mereology of the situation at hand. That is, as analysts we are concerned with changes in the control structures and umwelt structures (Figure 1).

Over a decade of doing micro-analytic studies of physics students engaged in activities and observing demonstrations, I have had many opportunities to ascertain three observations. First, students begin learning with domain ontologies that are not at all those that their teachers presume. Second, students evolve relatively stable language games, which, under favorable circumstances, are commensurable with those characterizing scientific communities. Third, activity is central to the establishment of domain ontologies and discourse via an evolutionary trajectory from ergotic/ epistemic to symbolic (hand, arm, and head) movements.

Evolving the Domain Ontology

The language games teachers want their students to develop do not make sense if students' domain ontologies do not support the kind of distinctions and theoretical descriptions required in the teacher's framework. The domain ontology is dependent on prior perceptual experiences and the articulations embodied in linguistic structure; both change slowly with experience and under the constraints of the physical environment (e.g., Pickering, 1995). (Churchland [1995] argues that humans as all dynamic learning systems [e.g., artificial neural networks] undergo radical change only infrequently but evolve along continuous trajectories; similarly, scientific communities seldom undergo scientific revolutions but rather change their knowledge in incremental ways.) That is, students do not come to the demonstrations and laboratory experiments, and perceive, in an instant, an ordered world neatly cut into relevant objects and events, each composed of more basic elements. Rather, beginning with a more global perceptual experience, students work out where relevant cuts can be made, what some characteristic features are, where changes occur, and so forth. This working out is achieved through action-perception-expectation interactions and evolves over time. The following three episodes all document how student ontologies evolve from experience rather than being immediately given to their perceptions.

Three students sit around a computer using a Newtonian microworld containing nothing more than a circular object to which two arrows are attached (Figure 2.a). The arrows can be modified in magnitude and direction. Hitting the "run" button, the system is set in motion. Students are asked to explore this microworld and, at the end, to provide an explanation of how it works; that is, they are to explain how the arrows are related to what happens to the circular object. Even in this, what might be considered a relatively simple system, students do not always agree on what is observed. Thus, in one instance they disagree on what happens to the situation on the left in Figure 2a. Glenn and Ryan suggested that the object moved immediately downward ("It goes straight down" "would go downward”). Elizabeth questioned whether it did not first move upward in the way displayed on the right in Figure 2.a (“Doesn’t it go backwards first?”). In the same way, the three students often disagreed as to different changing features and the invariants of the system (e.g., magnitude and direction of each arrow). In this situation, a teacher intervention designed to help students “see” what he saw brought about a change in the domain ontology identified and acted towards by students. Using a slow motion feature of the computer program, the initial upward movement became salient and part of their umwelt. All three students individuated it and subsequently characterized it in terms of an everyday description: “Everything that goes up has to come down,” “It’s like a hula hoop that comes back when you spin it,” and “reminds me of a yo-yo.”

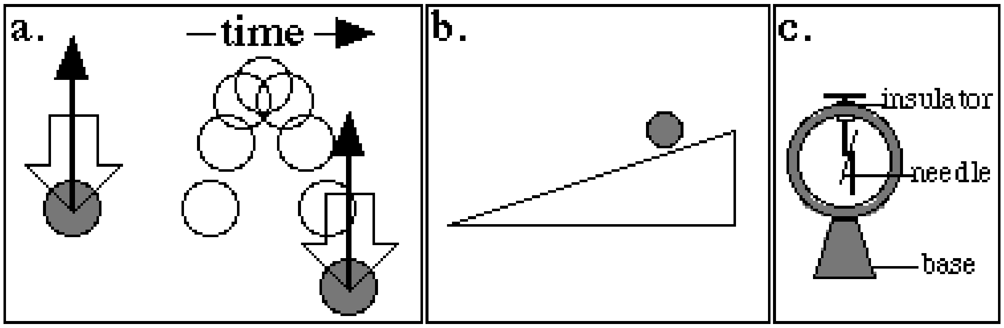


Figure 2. Situations observed by students. a. Output from computer-based Newtonian microworld. b. Solid and hollow cylinders and spheres roll down an inclined plane. c. An electroscope being charged and discharged.

In a similar way, Sean, a grade 12 student, observed a cylinder rolling down an inclined plane (Figure 2.b). He characterized the resulting motion as “constant velocity.” Following this event, Sean and his two peers observed this and other objects roll down the plane perceiving constant velocity for 16 times before revisiting his earlier description. Yet when he watched himself one week later on videotape, he expressed astonishment that he had characterized the motion in terms of constant velocity rather than as an instance of accelerated motion. It appeared as if the enunciation of the observational description fixed what they could subsequently perceive. In the same class, we found that students who watched the same demonstration actually expected and saw different types of motion events: Eighteen students saw motion and only five students saw no motion consistent with their teacher’s theoretical description.

Finally, students may work with instruments for extended periods of time before noticing a constitutive part of a piece of equipment. For example, to understand how an electroscope (Figure 2.c) functions, one needs to understand it in terms of two mereologies (ways of sectioning it into parts). As a mechanical device, the central suspension and the outer ring are fixed allowing the needle to rotate. As an electrical device, the outer ring is insulated from the central suspension by means of a plastic insulator into which the suspension is embedded. However, after working for four lessons using the device seven groups of grade 10 and 11 students were not consciously aware of the insulator. In all situations, students became aware of it in the same type of crucial incidence: A teacher asked them how the electroscope could be discharged. In all cases, students answered that touching the device anywhere could do this. Following the teacher's request, they touched a charged electroscope on the outer ring, an action that did not change the needle deflection. In all cases, one student in the group then came to identify the plastic as an insulator.

The point here is not that students see something in a way that is correct or incorrect. Rather, all three excerpts show that what students see is often not the same; their domain ontologies are different. If these differences went to go unchecked, it is likely that teachers' explanations do not make sense to students, or are adapted such that within students' ontologies, mereologies, and existing language games, they can be temporally adopted without too much strain. However, when students have extensive opportunities to engage each other, and when their task is to evolve common ways of describing and explaining what they observe—that is, when they are required to elaborate language games—such differences rarely ever go unchecked. The differences then become important sites for the negotiation of domain ontologies, mereologies, and language games (e.g., Roth, 1996b). Other constraints which exist mainly in the form of interactions with the teacher (or specific constraints that can be provided in computer microworlds and textbooks) which, under ideal conditions, allow the common language games to become more commensurable with scientific language games (Roth, 1995).

Students found out other characteristics of the electroscope through their interactions with the instruments. Thus, Marcel slowly approached a charged film to the plate on top of the electroscope (Figure 2.c) and intently observed the needle. From an observer perspective, as Marcel's hand with the film approached the instrument, the needle deflected about proportionately; as he increased the distance between film and electroscope, needle deflection decreased. Marcel repeated the increases and decreases of distance between film and materials for about two minutes, when he all of a sudden suggested to his peer group that he had found how the system worked. In his description, he linked the electrostatic properties of pushing charges with his film into the instruments with a corresponding mechanical deflection of the needle caused by a built up of charges. Here, the approximately linear negative covariation between his approaching the film and observed needle deflection became the basis for the theoretical description in terms of charges that were pushed about by the film and caused the changed deflections.

In this example, a new theoretical description for the electroscope arose from registering the covariation between an action and observation. In other instances, however, new perceptions were associated with variations in actions that had arisen from what appears to be a random variation in actions over time. Sometimes a new action stabilized as it proved successful and then gained a foothold in the activities of students. For example, during one period, Matt rubbed a transparency film on the table surface and brought it near the electroscope. The needle deflected. Without ever thematizing what had happened, and though nobody else had previously charged a film like this or told him about it, Matt charged his films for the next two periods. Soon after he had started it, two of his group mates changed how they charged their films, and finally all four around the table rubbed the films on the tabletop. Here, charging a film by rubbing it on the tabletop arose from a random variation. At no point during the two lessons is there evidence that any one of the four students is conscious of the new practice for changing transparency films.

Negotiating Language Games

In school classrooms that allow students some freedom to interact with their environments (peers, teachers) students evolve their own observational and theoretical languages (though these bear family resemblances with those that they use at the outset). Although students begin with different ontologies, they arrive, through their interactions, at shared descriptions and explanations. These interpretations are *interactively stabilized*, that is, they are grounded in social interactions. Other interpretations stabilize at first but are subsequently destabilized and abandoned; still other interpretations never find resonance within the group. Often, the outcome is commensurable with the scientific canon. In a series of studies, I showed how learning physics can be understood as the co-evolution of students' ontologies (worlds, umwelten) and their language games (e.g., Roth & Duit, in press); I used constraint satisfaction networks to implement individuals themselves connected into networks of individuals (network of networks).

When students are allowed to interact with some experimental equipment and with their peers (and teacher), tremendous changes can be observed as they establish their own observational (related to ontology) and theoretical descriptions. For example, Glenn, Ryan, and Elizabeth used 10 different terms for the outline arrow denoting force (Figure 2.a) before settling on "force," and 14 different terms before settling on "velocity" to denote the velocity vector. In the same class, other student groups went through similar length of working out the domain ontology and, in the course, a workable and successful language.

In a similar study concerning fundamental concepts in chaos theory, we found evolutionary trends in the language students used in their small groups and at the classroom levels (Roth & Duit, in press). At the classroom level, a refinement of the discourse related to deterministic systems and systems with limited predictability could be observed. This refinement pertains to the number of concepts employed and to an increased differentiation of the discourse with respect to the course content. The emergence of new discourse elements was tied to particular activities. Thus, the distinction between ideal models and observed real models of chaotic systems was particularly tied to an activity in which students explored, using a dynamic computer model, the impact of small variations in initial conditions and influences during their trajectories on the motion of a pendulum. Some of these new linguistic elements were stabilized and therefore became part of the classroom discourse, whereas others were discarded and never reused in future activities (or post-unit interviews). Thus, the development of talk in activity and talk at the class level interacted with each other in the form of “upward” and “downward” causation.

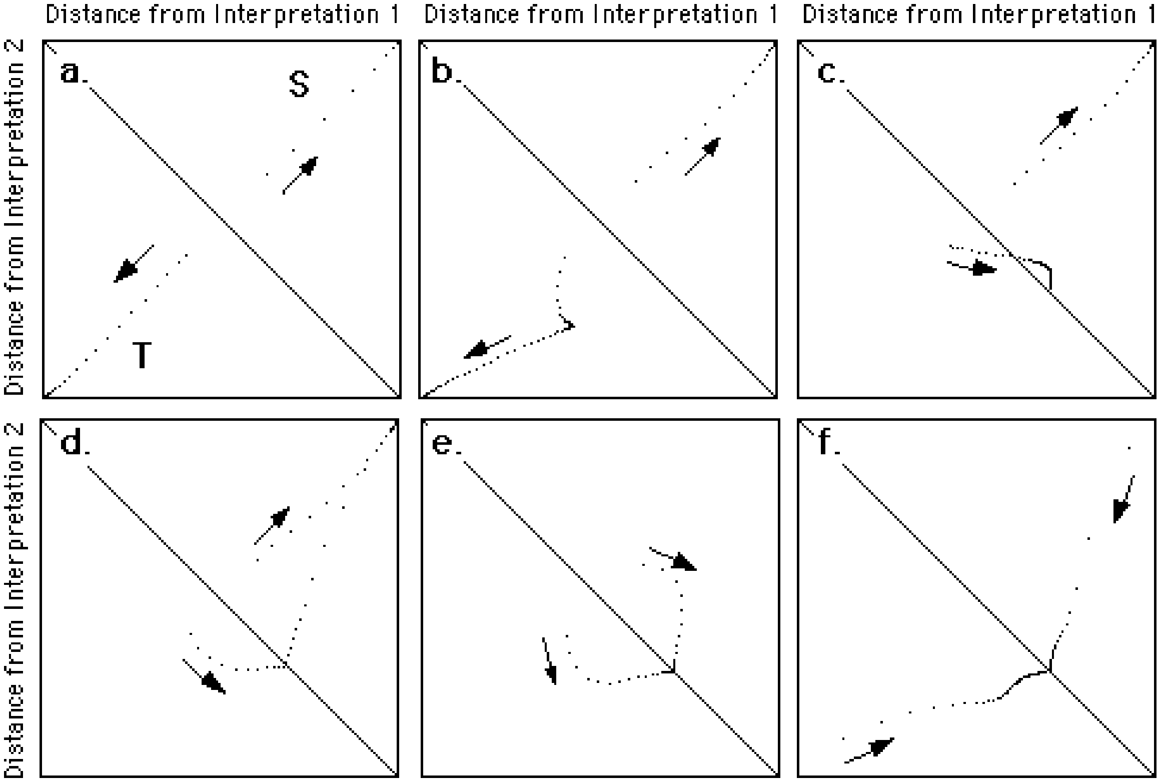


Figure 3. Results from an artificial neural network model of two subjects settling engaged in interaction. The closer together their starting points relative to Interpretation 1 and 2, the more similar the initial set of hypotheses supported by each. **a.** S and T do not influence each other. **b.** S has some influence on T causing him to waver. **c.** S has enough influence to cause T sustain both interpretations. **d.** S influences T to the extent that the letter first sustains both interpretations, to end only supporting Interpretation 2. **e.** S and T mutually convince each other to also support the other’s interpretation. **f.** Despite initially strongly favoring one interpretation, both end in support of both interpretations.

Figure 3 shows the results of modeling, using my own constraint satisfaction networks, the group dynamics during the negotiation of two different interpretations of an ongoing event. Each interpretation is a function of three hypotheses of which the two interacting agents in the present model are aware to different extent. However, because they interact with each other, each agent can influence the other. The final position each agent takes depends on the dynamic of the interaction, the strength they influence they exert on each other, and the extent to which the hypotheses support a particular interpretation or constrain the alternative interpretation. Whereas the students come to support alternative interpretations of the same situation in the first three panels (Figures 3.a-c), negotiations lead to commonly supported interpretations (and collections thereof) in the second tier of panels (Figures 3.d-f).

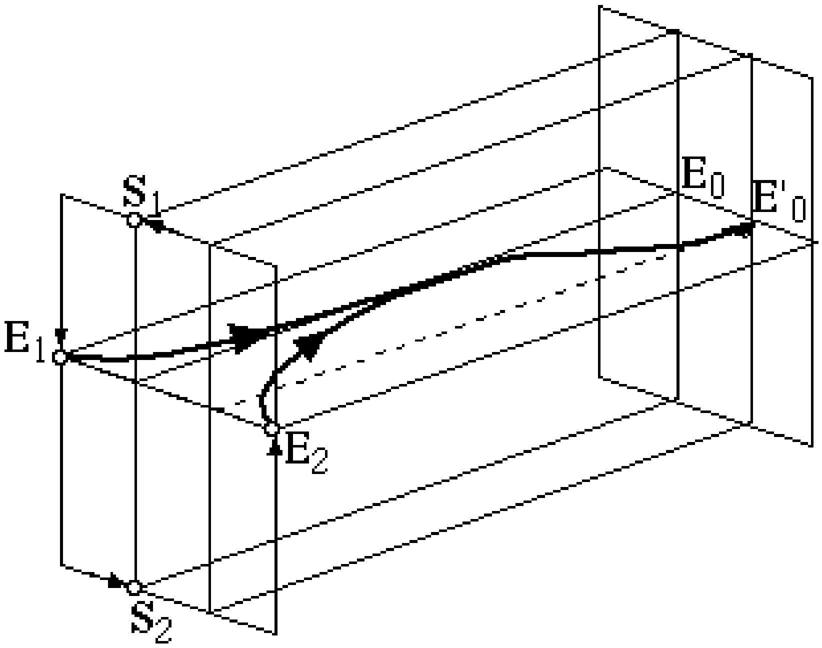


Figure 4. Communication system involving two subjects S_1 and S_2 generating discourse E_1 and E_2 in and about a common environment E (after Brier, 1998). Through their interactions (S_2 interprets E_1, S_1 interprets E_2), the two subjects eventually come to a common discourse and shared ontology (umwelt) E_0. Because of constraints in the learning environment (teacher, books, and tools), their common ontology and discourse changes over time to become, in many cases more commensurable with scientific discourse E'_0.

As pointed out, students may negotiate common ontologies, mereologies, and language games, but these may have little in common with those that currently reign among scientists. The collectively evolved language games may, as a function of other constraints in the setting (interactions with teacher, textbook, structure of equipment), further evolve. Figure 4 presents a summary of this research in physics classrooms in terms of the communicative systems presented by Brier (1998). In this model, two subjects S_1 and S_2 act towards (speak about) their respective umwelt in terms of discourse E_1 and E_2 (see arrows). Hereby, S_1 gets to hear and interpret E_2, S_2 comes to hear and interpret E_1. Because the two subjects assume to be in the same environment E, they negotiate differences between E_1 and E_2. (Such negotiations are seen to be especially necessary when they concern aspects of the physical world, and may be deemed unnecessary when the interactions concern differences over the aesthetic value of an art piece.) Through their interactions, the two subjects evolve a shared common umwelt and communicative system E_0. This development of shared interpretations is exactly that predicted in my computer models (Figure 3.d-f). In the case of my physics students, they will, over time and because of further constraints in the environment (e.g., teacher), approximate the communicative system E'_0 of currently accepted science (Figure 4).

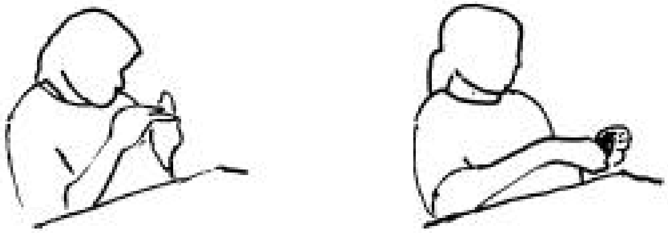
In this and the previous section, I provided empirical evidence for the way in which students develop common domain ontologies and language games, even when they begin with different ways of seeing and talking about the world at hand. Fundamental for such a development to occur is for subjects to assume that they inhabit the same environment and to be willing to talk about it in common terms. One may raise the question how we get from structuring the world through activity to describing it in terms of signs (i.e., language) that frequently bear an arbitrary relation to the things they are about? In the next section I provide evidence from my research that suggests that bodily movements related to activity may change into symbolic bodily movements (gestures). Symbolic movements are then sites for the emergence of other symbolic modalities (language, drawings).

From Acting to Gesturing and Speaking

In the classrooms where students interact extensively with materials (and material signs such as drawings, graphs, and semantic networks), a communicative means other than language emerges from the activities: gestures. In fact, gestures are not merely coproduced but are associated with three important ontogenetic evolutions. First, they arise directly from the activities in a transition from ergotic/ epistemic movements, which subsequently transform into gestures, that is, symbolic movements. Second, they arise prior to language and are used as the primary symbolic form. Third, they decrease in their temporal advance and importance as language takes on an increasing amount of the representational (symbolic) function.

Gestures allow students to construct complex explanations even in the absence of scientific language. In this, gestures serve to represent aspects of the communicative content or to point to entities in the world that represent themselves. Gestures allow the coordination of phenomenal and conceptual layers of content. The phenomenal layer (entities, actions) provide the basis on which conceptual layers can be added, but indexical and iconic gestures provide the “glue” for this layering to be successful. The time for the situated construction of an explanation decreases and speech increasingly takes over the representational function. (a) There is a decrease in the temporal decalage between gesture and equivalent verbal representation of content or (b) long pauses with gesture and utterance overlapping.

Figure 5 shows an example of how gestures are used during a transitional period. Here, Jessica is asked at the end of a lesson to produce an explanation of static electricity. Prior to the excerpt, she has identified the pen in her left hand as standing for a transparency film, the pen in the other hands as representing a piece of cloth. As she describes that these materials have to be rubbed, she enacts the rubbing. But rather than using the original materials, she uses the pens to stand in for them. Up to this point, her explanation involves a description of macroscopic events and the establishment of sign-referent relations. Her subsequent utterances identify what happens at an atomic level (Line 2). As she places the fountain pen, she pulls off the cap and then refers to the pencil-pen body combination on the table as “negatively charged” and to the pencil-pen cap combination in her left hand (which she moves far to her left) as positively charged (Line 3). Here, the macroscopic materials are represented in the pencils; the microscopic charges in the fountain pen. As she separates the pencils, the microscopic entities also get separated.



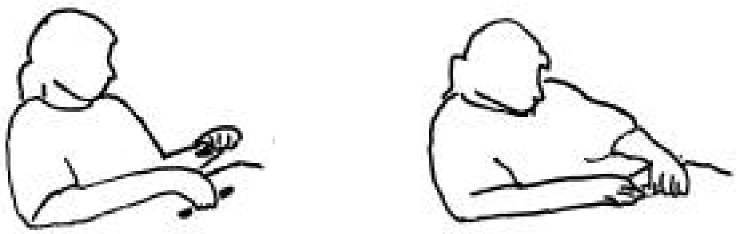
G:

G: [_rubs [picks up 3nd pen

G: [_

J: Und wenn man die [r::eibt (0.93) [mit dem hier (1.02)

: And when one them now rubs with this one here



G:

G: [_places pen [places body [_pulls pen cap [moves hand

J: [Dann entsteht [hier (0.65) [viel negative Ladung [und hier ist

: Then is created here a lot of negative charge and here is

G:

G: _ _

J: positiv geladen. Und darum ziehen die sich an.

: positive charge. And therefore attract they each other.

Figure 5. Jessica describes and explains the generation of static electricity. The gestures can be traced to the action of rubbing. On top of what she has experienced, she layers the atomic-level theoretical language including metaphorical gestures of separation. The pen has the role of representation in the world.

This is a complex event with multiple representations in speech, gesture, and in material objects. Here, the gestures iconically represent the rubbing of the film with the cloth; at a second, conceptual level that can be understood as layered on top of the phenomenal level, the gestures iconically and metaphorically represent separation of charges. The pens also do representation work. When students denote objects in the world as placeholders for words and concepts they do no longer have to represent them in words. Rather, they may point to them whenever necessary; because of the copresence of the other speakers, pointing is sufficient and talking made unnecessary when entities that are accessible to all “go without saying.” Finally, speech represents aspects of the focal situation. Distributing communication across different modalities decreases the cognitive load on working memory that has a limited capacity for assembling speech.

In preceding episodes (not shown here), Jessica gestured the rubbing and separated the charges in gesture before she actually talked about it. In this classroom gestures normally preceded speech between 400 and 1400 ms; in some cases, there were delays of more than 2 seconds. At this stage, however, toward the end of the second lesson after having charged a large number of objects by various means, gesture and description of charging largely coincided. Parallel with the decrease in temporal delay was a decrease in the amount of time taken to develop a local interpretation. Thus, Jessica explained an experiment a second time for a peer who had been absent. Here explanation decreased from nearly 20 seconds to 11 seconds with a corresponding decrease in the number of gestures; an increased amount of her description was rendered in the utterance. Often, the emergence of new language games was associated with the use of the actual materials in the descriptions. These were later substituted by placeholders (as in Figure 5), and then completely expressed either in gesture (an open palm denoting a [charged] transparency film) or by drawings and words on paper.

Ultimately, given the pressures on students to express themselves in textual forms when it comes to oral and written examinations, it is not surprising that these pressures favored the development of textual forms of expression. Situationally (in schools) more viable communication patterns in the form of verbal and written language emerge. Furthermore, symbolically enacting previous movements designed to operate on the environment (i.e., ergotic movements) takes time, more than an uttering an appropriate word. Furthermore, moving around objects that stand in for the entities communicated about also puts constraints on the brevity of expression.

Discussion

In this article, I present empirical examples from a large database on student learning. These and many other structurally identical examples in my database portray aspects of cognition and learning that undermine many of the current assumptions in education and cognitive science. These are assumptions based on ontologies of worlds as we find them in mature adults. First, students first perceive physical events and materials in holistic ways often different from the ways adults and scientists see them, and evolve domain ontologies as part of their structural couplings with their settings. Second, when students are given the opportunities to talk with peers as they engage in the laboratory activities, they evolve common language. This common language is often different from that used by informed teachers and scientists, and there are often different language games that evolve in different groups within the same classroom. Through structural constraints, these different language games can be made to converge within the classroom and toward other existing ones. Third, when students engage in activity that they are subsequently to explain, they often use gestures in their initial attempts to observational and theoretical descriptions. These gestures arise directly from their activities with which they stand in an iconic relationship. In the course of the students' development, the frequency of gestures decreases, the delays between the gestures and later-occurring speech decrease, the reliance on material representations and deictic gestures decreases, and there is an increased amount of representation in speech.

The literature on the value of science laboratory inquiries is ambiguous—many science educators seem to doubt that laboratory activities contribute much to students' learning (e.g., Tobin, 1990). Results of the studies from which the present examples were taken suggest otherwise. If students are allowed to engage in laboratory activities and in constructing observational and theoretical descriptions while still in the presence of the materials, they can embark on trajectories of learning science with evolutionary tendencies. Over time, their domain ontologies and the language games (observational, theoretical) about the focal entities and events change and frequently become commensurable with those that characterize science and scientists. The presence of the materials, in and as external representations, indexical ground, and reference for iconic gestures supports the emergence of language by facilitating the transitions from ergotic/epistemic to symbolic movements which are the basis for more abstract forms of communicating (signing).

In this way, cultural reproduction rides on cultural production, and is brought about by specific constraints such as teacher and textbooks. Thus, ontogenetic development is functionally constrained by the material world and culture. The material world considerably constrains the ontologies and observational descriptions; cultural constraints operate largely on the theoretical descriptions. In the larger scheme of things, the language games students learn in schools have little adaptive value after school both in the short run and in the long run. It is therefore not surprising that school physics meets with relatively little success in assisting students to develop understandings that are commensurable with those of physicists. Rather, sticking to worlds by and large characterized by routine word problems, language games, and visual displays, students can survive the naming game required to get a decent grade in their course requirement without having a substantive change on the ways they experience and describe the world around them.

We may ask whether similar results could be observed in other types of classes. At this point in time, I have few other data available. One of my studies was concerned with grade 8 students' learning of ecology. The students conducted research of their own design to find out as much as they could about some natural environment that they had staked out. Although they began by noting "there is nothing to see" and "there is nothing to be researched," these students evolved highly developed ontologies and signing practices in the course of their research (e.g., Roth & Bowen, 1995). I would hypothesize that similar observations would be made as long as two conditions are fulfilled. First, students must be able to move about and manipulate their environment to create differences that make a difference. Second, the learning environment should embody (ecological) constraints that operate such as to make students more successful when they communicate and thereby evolve common language games.

The work reported here also contributes to a long standing problem in philosophy and artificial intelligence, the “grounding” or “binding” problem. This problem concerns the question how mind is connected to the body; in a reframed version, the problem is one of the relation between a functionalist view and a phenomenological view of humans qua organisms (Brier, 1998). In the approach taken here, which inherits much of its structure from the phenomenology of perception (Merleau-Ponty, 1945) and functionalism (e.g., Bateson, 1972), the problem is dissolved for each individual experiences with his/her body which is always and already part of the material world. There is a bodily integration of action (ergotic, epistemic) and perception, which constitutes the ground (the very possibility) for having the kind of experiences humans have. Out of this integration, ergotic and epistemic movements lead to symbolic movements (gestures), movements that come to stand for others which have previously occurred. These movements are the basis for a transition from standing in an iconic relation with the entities they stand for to an abstract relation in the sense that they could also stand for something else. Here, a gesture becomes sign of signs. The antinomy between matter and mind is resolved. Matter self-organizes into organisms that move, which self-organize into mind using earlier evolutionary achievements as their elements.

We can also frame this grounding process in terms of a shift from ‘sign games’ to ‘language games’ (Brier, 1995). Following Bateson, Brier suggests that information is a difference that makes a difference. Differences become information when they are registered and interpreted as signs. Organisms note differences even in the absence of a conscious awareness and therefore engage in sign games (e.g., mating or nest building). In the present situation, differences are processed first (or in parallel) at a physical level and are part of sign games. As gestures, which already are subject to syntactic constraints, the same movements then provide a transition from sign games to language games.

Self-organization occurs within the structurally coupled system that can heuristically be divided into organism and environment (as long as we do not forget that they really cannot be thought separately). However, the organism does not “see” some abstract environment; rather, it orients itself towards its own “umwelt.” At an ontogenetic level and applied to classrooms, we should think about learning environments in terms of the students’ umwelten, because these contain the structures that students perceive and act towards. It is these umwelten that change as students interact with their peers, teachers, and material structures.

There need to be more studies that explore salient cognition from two sides. On the one hand, we need synthetic studies that model salient phenomena in ways that are not incommensurable with empirical evidence. The brittleness of classical artificial intelligence models should have been a hint that they inappropriately attempt to capture and explain human behavior. Artificial neural network models have been much less brittle and have other features that are more consistent with the way organisms function and learn. The most promising systems are those that, like Steels’ robots (see Brooks [1995] for another successful project) evolve and learn through interacting in adaptive ways with some universe. On the other hand, we need careful, micro-analytic studies and phenomenological studies of real people without prematurely forcing descriptions into the Procrustean beds of traditional perspectives on what knowing and learning are about. This requires a systematic suspension of judgment (the phenomenological ‘epoché’) which, as a theoretical physicist at the renowned Princeton Institute of Advanced Studies suggested is the only way to make the sciences more philosophic and philosophy more scientific (Hut, 1999). Ultimately, the results of the two forms of research need to approach each other. Research that is inconsistent with experience cannot be a good explanation and only good explanations help us further develop our understanding of experience.

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