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## **Learning to Use Scientific Concepts**

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In their abstract, Treagust and Duit ask “whether conceptual change can provide a powerful framework for improving instructional practice in such a way that students’ levels of scientific literacy are significantly increased.” And later in their paper they quote PISA 2000’s definition of scientific literacy as “the capacity to identify questions and to draw evidence-based conclusions in order to understand and help to make decisions about the natural world and the changes made to it through human activity” [78].<sup>1</sup> Since both quotations are concerned with the achievement of scientific literacy, although addressed from very different perspectives, together they provide a framework within which to consider how far the research on conceptual change has contributed to the achievement of PISA’s goals for scientific literacy. My question is: Is the attempt to change students’ concepts the best way to proceed?

As did Treagust and Duit, I want to start by “considering the nature of conceptions.” What is at issue, as I see it, is the ontological status of concepts (or “conceptions”). Throughout their paper – and in the Conceptual Change (CC) literature more generally – students are treated as having concepts. This implies, first, that those concepts are relatively stable mental entities and, second, that they are possessed in the same sort of way that other entities might be said to belong to individuals. However, as I shall try to show, the assumptions underlying such locutions are seriously misleading. Concepts are not mental objects, nor do they belong to individuals.

To elucidate this second point, it is useful to make a clear distinction between individuals’ knowing and what, within the scientific community, is taken to be known. While knowing is always situated in place and time and occurs as part of a particular

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<sup>1</sup> Throughout the paper, numbers in square brackets refer to the sequential number of the paragraph in Treagust and Duit’s paper.

activity, knowledge, in the sense of what is known, is the institutionally sanctioned, accumulated outcome of the formal procedures whereby what particular individuals claim to know as a result of their research is critically evaluated and formally documented according to the historically developed practices of the professional organizations to which they belong. Concepts are thus collaboratively produced constructs that constitute the realm of “what is known.” They are symbolic formulations that can be located in texts of various kinds whose authority is independent of the particular individuals who constructed them. However, although accepted as authoritative at a particular moment, concepts are not unassailable. Indeed, the history of science shows that all concepts undergo revision and change over the long term, as a result of the continuing attempt to improve on what is known. Furthermore, what is known at any time is independent of any particular knowers. As Polanyi points out with respect to scientific knowledge,

Nobody knows more than a tiny fragment of science well enough to judge its validity and value at first hand. For the rest he has to rely on the views accepted at second hand on the authority of people accredited as scientists. (quoted in Olson 2003, p.67)

Popper (1972, 1978) referred to concepts, along with other cultural creations, as “third world objects”, distinguishing world 3 from the other two worlds in his model: World 1, the physical universe; and World 2, the world of conscious experience.

I assert that we can, and that indeed we must, distinguish sharply between *knowledge in the subjective sense and knowledge in the objective sense*. Knowledge in the subjective sense consists of concrete world 2 thought processes, with their correlated world 1 brain processes. (1978, p. 156)

I suggest that we must distinguish between world 2 *thought processes* and world 3 *thought contents*. The thought processes are concrete, in the sense that they happen to certain people on certain occasions; at a certain place and at a certain time. .. By contrast, there are the thought contents, which are abstract world 3

objects. (1978, p.160)

What Popper does not sufficiently emphasize, however, is that the origin and continued existence of world 3 depends on its embodiment in people's concrete activity and the artifacts produced by their labor in world 1, and equally on the thinking processes that he distinguishes as world 2. Nevertheless, the distinction he makes between world 2 and world 3 is critical for an understanding of what is involved in "conceptual change."

The researchers whose work is summarized by Treagust and Duit are concerned with the relationship between worlds 2 and 3, but in their way of thinking about it, they tend to elide Popper's distinction, as is apparent when they write of students "having concepts." That is to say, they fail to make the distinction between students' world 2 concrete thinking processes and the world 3 contents of these processes as these are interpreted on the basis of their utterances on particular occasions. In order to understand conceptual development, therefore, it is necessary to investigate the ways in which these third world objects are used in different activities and how learners come to master the uses to which they are put.

### **Concepts as Tools for Action**

Much work in philosophy in the early part of the 20<sup>th</sup> century was concerned with concepts as used in propositions and with the conditions under which propositions could be judged to be true or false. However, in the William James Lectures delivered at Harvard University in 1955, J.R. Austin proposed a very different direction for inquiry. In *How to do things with words* (1962), he argued, first, that expressing propositions was not the only function of sentences and, second, that sentences only have consequences when they are used, as utterances, to perform various types of action on particular occasions. This idea was not new – it was central to the work of Bakhtin and his circle (Voloshinov 1973; Bakhtin 1986) – but it did bring about a significant change in linguistic philosophy in the English-speaking world. However, what is important about the line of work that Austin initiated in the present context is the shift it brought about from thinking of concepts and propositions as ahistorical and decontextualized to the recognition that they are created and used *to get things done* on particular occasions.

In the philosophy of science, too, there was a comparable move. Considering the role of models and representations in scientific understanding, Wartofsky (1979) argued strongly that the primary emphasis should be placed not on representations but on the activity of representing. Representing, he proposed, is a fundamental human activity; it is something we do as an essential means of perceiving and knowing and it is central to all forms of action. Representing is making use of some artifact to “suggest how we should proceed in structuring our understanding of the world and of ourselves” (p. xv). To elucidate this general claim, he proposed a three-way classification of artifacts. Primary artifacts are those that result from a transformation of part of the material environment for some practical purpose, for example hammers, pencils, and computers; they can function as representations in the sense that they “carry” information about their use and their mode of production. Secondary artifacts, by contrast, are semiotic objects (including utterances) created for the purpose of managing the production and use of primary artifacts and for transmitting the knowledgeable skills involved from one generation to the next. Finally, tertiary artifacts are the outcome of imaginative activity in science or the arts, in which the formal properties of secondary artifacts are manipulated without immediate or direct application to the world of practical activity; these are exemplified by the scientific models and theories with which Wartofsky was most concerned.

In categorizing models and theoretical representations as tertiary artifacts, Wartofsky was making a claim similar to that of Popper, who situated “conjectures and theories” in world 3 and described them as potential “instruments of change” (1978, p.154). However, Wartofsky also emphasized their material embodiment as artifacts, which, through continued use, “can come to color and change our perception of the ‘actual’ world, as envisioning possibilities in it not presently recognized” (1979, p. 209).

According to the preceding account, conceptual tools play a role in almost every activity. However, they are not all of the same kind, since they were created for different purposes. Which conceptual tools are most appropriate on any occasion depends, therefore, on the nature of the problem to be solved. While the design of a vehicle to be powered by a renewable source of energy would certainly require the ability to coordinate the use of a variety of concepts developed in different fields of scientific research, the problem of how best to help customers use and maintain the product they

bought would require a different range of concepts, derived from more practically oriented activities. Similarly, while a nutritionist may need to use concepts developed in the field of biochemistry to advise on a healthy diet, a supermarket shopper uses less technical concepts in purchasing the ingredients for the family dinner.

This argument can be extended to problem solving in the classroom as well, as will be illustrated below. For example, while, to solve certain types of problem, it may be necessary for students to use concepts of force and motion, these concepts are not necessary in constructing a swing for the playground – although, as Wartofsky implies, the swing, once constructed, could usefully serve as a means of exploring the explanatory power of these scientific concepts. It follows, therefore, that no particular set of conceptual tools is universally best for all occasions and, thus, that it is inappropriate to categorize students' use of particular concepts as correct and others as misconceptions independent of the activity and problem to be solved (Wertsch 1991).

Treating concepts as tools for use brings us back to the issue of the different ways in which the part played by concepts in problem solving is conceptualized. In the literature on conceptual change, students are frequently described as having correct or flawed conceptions or, as in Treagust and Duit's overview, conceptions are "regarded as the learner's internal representations." In either case, conceptions are treated as having a continuing existence independent of occasions of use. However, the evidence for the existence of conceptions can only be found in particular acts of representing an event or relationship as part of some particular activity. Furthermore, as is seen in extracts from some of the interviews that the authors cite, students may produce a number of different representations in a short period of time as they attend to different aspects of the presented problem. It seems more appropriate, therefore, following Popper's distinction between thought processes and thought contents, to treat representations as thought contents that are formulated or constructed in the moment according to the perceived demands of the situation rather than as reproductions of some already existing internal objects.

In sum, in representing their understanding, the concepts that students draw on and use in such acts are world 3 objects, which exist either in external material/semiotic representations, such as diagrams, equations, written texts or spoken words, or internally

as memories of occasions when such external representations were previously used by self or others for some particular purpose. But whichever source – external representations or memories of different kinds – is drawn upon to mediate the current problem-solving goal, an active process of construction is required – a transaction between the problem solver, the conceptual tools available, and all the other affordances and constraints of the immediate situation, of which the utterances and actions of other participants are an integral and consequential part.

### **Language and Conceptual Development**

Most of the evidence concerning students’ “conceptual development” comes from their utterances, where utterances are understood broadly as meaning-making acts in whatever modality is selected.<sup>2</sup> This applies both in the field of developmental psychology as well as in studies of conceptual change. It therefore seems important to look more closely at the relationship between uttering and thinking. Clearly, to provide an adequate explication of the changing role of utterance in intellectual development is beyond the scope of this paper;<sup>3</sup> however, in the following, I will attempt a sketch, adopting Vygotsky’s (1981) “genetic”<sup>4</sup> approach.

In the long history of our species, long before speech developed, early humans had learned how to make use of and improve found tools; they had also developed ways of passing on tool-making practices to successive generations. Donald (1991) argues that this almost certainly required mimetic communication, by means of demonstration,

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<sup>2</sup> Gestures and other forms of non-verbal action, including the making of visual representations, frequently accompany linguistic utterances and, on occasion, substitute for them in interpersonal interaction (Crowder, 1996).

<sup>3</sup> See Nelson (2007).

<sup>4</sup> Vygotsky (1981) argued that, in order to understand the current state of some aspect of development, it is necessary to study the history (genesis) of that development.

gesture and other preverbal acts, through which thinking processes such as those involving using found objects as tools and considering means-end relationships were enacted intermentally – between people. Then, when it evolved thousands of years later, the capacity for speech was utilized and developed to build on this meaning-making foundation, enabling finer distinctions to be made in categorizing aspects of the material world in space and time and in deliberating about cause and effect, intended actions and their anticipated consequences. Knowing continued to be closely tied to situated collaborative activity, but with the additional possibility of speculation in advance of, and reflection during and after, action through the medium of spoken discourse. These shared meanings, co-created in intermental discourse, were then appropriated to function as a resource for intramental functioning in the discourse of inner speech (Vygotsky 1987). Finally, over time, some of the cultural ways of explaining the history and achievements of the group became somewhat stabilized as world 3 objects in the narrative genres of myths and epic poems that persisted over generations through ritual and the oral tradition (Bruner 1990).

However, about 4,000 years ago, in some cultures, this oral mode of knowing was gradually but dramatically supplemented by the invention of writing, which proved to be a significantly more powerful mediator of knowing. Written texts are more permanent than speech and they are also materially independent of the one(s) who produced them. But most important in relation to the enhancement of knowing is that, as Olson (1994) points out, "What literacy contributes to thought is that it turns the thoughts themselves into worthy objects of contemplation" (p.277). Furthermore, for those who are literate, writing serves as an external memory, making possible the archival collection of information and the cumulative development of understanding. By the same token, writing and other written notational systems provide a more effective material medium in which world 3 objects can be preserved, revised, and consulted when required. In these ways, writing made possible the development of what Donald (1991) calls a "theoretic culture."

Turning now to the ontogenetic level of development, it can be seen that, in significant ways, each child's development recapitulates the cultural-historical development of our species. While immediately situated in a particular moment in the

historical development of a particular society and, within that, of a particular family – with all that entails with respect to the humanly shaped environment in which he or she grows up – each child’s development progresses from preverbal mimesis to speech and, in literate cultures, to the mastery of literate ways of representing meaning (Nelson 1996; Wells 1999). From birth, all infants are surrounded by a multitude of cultural artifacts that, to a considerable degree, determine what can be noticed, investigated, and jointly attended to with caregivers and other members of the immediate community. It is in and through participation in such joint activities, and in the linguistic interaction that is almost always a constituent part of them, that children learn their first language and, in the process, appropriate their community’s ways of making sense of experience. For, as Halliday points out, "Language has the power to shape our consciousness; and it does so for each human child, by providing the theory that he or she uses to interpret and manipulate their environment" (1993, p.107).

Viewed from this perspective, concept learning is an integral aspect of learning to talk. This is because, while most utterances that a child hears refer to some particular event or state of affairs, the lexical items – nouns and verbs – that are used in these utterances name categories rather than particular instances. Thus, when a mother says, “Look, I can see a horse,” she is not only seeking to direct the child’s attention but is also identifying the animal in question as a member of a particular class of things which are subsumed under the concept “horse”. Perhaps surprisingly, young children seem to have little difficulty in grasping this categorizing function of words; however, they do have some initial difficulty in discovering the extension of particular words/concepts. In an article entitled “Some aspects of the conceptual basis for first language acquisition,” for example, Eve Clark (1974) describes how one child she studied initially used “hosh” for all large animals seen on a visit to the zoo. However, with the addition of further animal names to her vocabulary, she fairly quickly learned to assign different animals to the accepted conceptual categories of her culture.

Most new words, and the class concepts that they denote, are learned spontaneously in the course of everyday activities; only occasionally are they deliberately taught. In fact, new words are typically encountered in contexts in which their meaning can be inferred from the situation that is the focus of joint attention. The following is a

typical example of such incidental opportunities for learning; it occurred when Mark was about 20 months old.<sup>5</sup>

Example 1.

Mark: (looking out of the window at some birds feeding in the garden)  
 Jubs [birds], Mummy  
 Mother: What are they doing?  
 Mark: Jubs bread [Birds eating bread]  
 Mother: Oh look! They're eating the berries, aren't they?  
 Mark: Yeh  
 Mother: That's their food . they have berries for dinner  
 Mark: Oh

(Wells, 1986, p. 22)

In this brief conversation, the mother recategorizes what the birds are eating and makes several conceptual connections: “berries” are categorized as [a type of] “food”, a more inclusive concept, and food is what Mark eats when he has “dinner.” It is in conversations such as this that children learn to use thousands of concepts that are important for making sense of the situations that arise in everyday life in their homes and communities.

A similar making of connections occurs in the following example, but because the child in question was considerably older, the mother's language is more complex and used with a more deliberately instructional intention. As James, age 5, comes into the kitchen, his mother has just taken some cakes out of the oven. There is a loud, metallic

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<sup>5</sup> In this and the following transcript extracts, the following conventions apply:

[ ] enclose interpretations and contextual information; < > enclose segments where the transcription is in doubt; \* indicates an unintelligible word; CAPS indicate a segment spoken with emphasis; underline indicates segments spoken simultaneously; . a period marks approximately one second of pause.

"Crack."

Example 2

James: Who did that?

Mother: I expect it was that tin contracting

James: Which tin?

Mother: The one with your pastry in

James: Why did it make that noise?

Mother: Well, when it was in the oven, it got very hot and stretched a bit .

I've just taken it out of the oven, and it's cooling down very quickly, you see, and that noise happens when it gets smaller again and goes back to its ordinary shape

James: Oh! was it a different shape in the oven?

Mother: Not very different . just a little bigger

James: Naughty little tin . you might get smacked . if you do it again

(Wells 1986, p. 22)

In this example, the conversation is initiated by a question, as James asks for an explanation for the unexpected sound he has heard. His mother, bearing in mind his age and probable level of comprehension, offers an explanation in terms she thinks he will understand. She uses the scientific term, "contracting," and then, following James's request for more information, provides a gloss on the meaning of the technical term in the form of a narrative account of the process involved and its cause. In so doing, she makes use of a number of "everyday" concepts, such as change in temperature ("get hot," "cool down"), change of shape, difference in size, in order to explain the scientific concepts of expansion and contraction. James's final comment is interesting, however, in that he introduces an affective concept into the situation; the tin is treated as a moral agent who has transgressed the expected order of things. This is apparently of more immediate significance to him than the scientific aspect of his mother's answer to his question. Nevertheless, it is likely that, because his mother explained the sequence of events that is captured by the concept of contracting in the context of the surprising "crack" sound he heard, the technical term "contracting", and the mother's explanation will remain associated in his memory. So, when he hears the word again, he may remember this total

experience and use it to make sense of the new occurrence of the word-in-context.

Both the preceding examples were taken from spontaneously occurring conversations in the years before the children concerned started school. However it is important to stress that this sort of situated spontaneous concept learning continues throughout the life-span without the need for formal instruction (Luria 1976; Cole 1996). In fact, most of our thinking in daily life is carried out with the use of everyday concepts, for, as Bruner puts it, our ways of making sense of experience are “rooted in a language and a shared conceptual structure that are steeped in intentional states – in beliefs, desires, and commitments” (1990, p.14).

However, in contrast to such “everyday” or “spontaneous” concepts, which may differ from one culture to another, there are also concepts of a more abstract kind. Of course, all concepts are abstractions, but most denote features of the perceptible world of everyday experience. However, there is a class of abstract concepts that have been deliberately developed to aid in explaining events and relationships that are not directly perceptible. Halliday (1988) attributes the appearance of these concepts/words to the development of a new way of using language in order to report the conclusions drawn from observations and experiments in the natural sciences. Symptomatic of this new register was the replacement of active clauses by nominalizations (Halliday and Martin 1993), thereby generating an indefinitely large number of apparently new concepts, such as “calcification,” “immunization,” “randomization” and so on. These technical neologisms and concomitant grammatical modifications, together with the incorporation of mathematical and scientific systems of notation, potentiated the reporting of observed or hypothesized events and the causal relationships involved more succinctly and unambiguously than was possible in the language of everyday speech.<sup>6</sup>

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<sup>6</sup> These sentences are so written as to exemplify the characteristics of the new linguistic register discussed. Halliday (1993) uses the terms “synoptic” and “dynamic” to contrast the language of science with everyday language. Bruner (1986) makes a similar distinction between “paradigmatic” and “narrative” modes of meaning.

When Vygotsky (1987) called these “scientific” concepts, in contrast to “spontaneous” concepts, what he had in mind was the broader range of what might be called “schooled” concepts, of which those developed in the sciences are only a subset. In writing about these two types of concept, Vygotsky distinguished the learning of the latter from two perspectives. First, scientific concepts are systematic, in the sense that any such concept exists in an organized system of other concepts of greater or lesser generality as, for example, in a taxonomy; this leads to implicational relationships between concepts and the fact that any scientific concept “can be represented through other concepts in an infinite number of ways” (p.226).

Learning to use scientific concepts also differs from the learning of spontaneous concepts in terms of what it requires on the part of the child. The latter concepts are described as “spontaneous,” in part, because, unlike scientific concepts, their learning does not involve conscious awareness or voluntary control. However, by the time the child starts school, these intellectual abilities are beginning to develop and it is through instruction of a systematic kind that scientific concepts gradually come to be used appropriately. Of the development of scientific concepts, he wrote: “Only within a system can the concept acquire conscious awareness and a voluntary nature. Conscious awareness and the presence of a system are synonyms when we are speaking of concepts” (p. 191). In other words, “scientific concepts differ from spontaneous concepts in that they have *a different relationship to the child’s experience*” (p. 178, emphasis in the original).

While Vygotsky clearly makes a strong distinction between spontaneous and scientific concepts and how they are learned, he nevertheless sees them as interdependent in the child’s overall development. “The development of scientific concepts will depend directly on a particular level of maturation of spontaneous concepts ... On the other hand, the emergence of [scientific concepts] will inevitably influence existing spontaneous concepts” (p.177). For him, therefore, the task of the teacher is not to evaluate individual conceptions as correct or erroneous/misconceived, but rather to help the child, through instruction with respect to the relationship between concepts within a system of concepts, to develop conscious awareness and voluntary control of his or her own thinking. “When this structure has been mastered, the child can reconstruct or reform the structure of all

previously existing concepts on this foundation” (p. 231) (Cf. Smith, diSessa et al. 1993).

Throughout his writing, Vygotsky treated concepts as equivalent to word meaning: “The development of concepts represents the semantic aspect of speech development. Psychologically, the development of concepts and the development of word meaning are one and the same process” (1987, p. 180). It is not surprising, therefore, that he conceived of instruction with respect to scientific concepts as being largely of a verbal nature:

The teacher, working the school child on a given question, explains, informs, inquires, corrects, and forces the child himself to explain. All this work on concepts, the entire process of their formation, is worked out by the child in collaboration with the adult in instruction. (1987, pp. 215-216)

While this description may today appear overly dominated by teacher talk, Vygotsky was surely right to place the emphasis on explaining. Nevertheless, it is not so much by explaining the concept itself that the child learns, I suggest, as by trying to use the concept in order to explain some problematic event or state of affairs in collaboration with others. As Popper suggests,

We can grasp a theory only by trying to reinvent it or to reconstruct it, and by trying out, with the help of our imagination, all the consequences of the theory which seem to us to be interesting and important... One could say that the process of understanding and the process of the actual production or discovery are very much alike. (Popper and Eccles, 1977, p.461)

In schools, it is typically the teacher who does most of the latter kind of explaining, while the student is expected to listen and remember. It is in reaction to this common practice that Lemke (1990) argues:

Just as with learning a foreign language, fluency in science requires practice at speaking, not just listening. It is when we have to put words together and make sense, when we have to formulate questions, argue, reason and generalize, that we learn the thematics of science. (p. 24)

In the following section, I will consider some examples of students' use of concepts in solving problems posed in science classes in the middle years of schooling.

### **Students' Use of Concepts in Science Activities**

The first example comes from a grade six class, in which small groups were planning practical projects to explore different ways of measuring the passage of time. One group, which was planning to make a sundial, was meeting with me [the visiting teacher] to discuss their progress to date. They had already cut a disk of wood and were preparing to mark the hours round the circumference when the teacher poses a question. Since the shadow on a sundial moves around an arc in relation to the position of the sun in the sky, which suggests that the sun is moving round the earth, he wanted to check that the students understood the accepted relationship between earth and sun.

Example 3.

Teacher: OK, so what makes the shadow move?

Lionel: The sun

Alon: When the sun moves or the earth moves

Teacher: Well which?

Both: The earth moves

Alon: The sun stays in one place and when-

Lionel: The earth- . OK here's the sun- it goes this way . if the earth moves here then it will go this way

Alon: No it won't

Lionel: Huh?

Alon: The sun stays in one place . the earth moves around.

Lionel: That's what I said

[7 seconds argument over who said what. Alon then takes a ball to represent the earth in relation to the overhead light]

Alon: The sun is here ok? . and the earth will just- it will turn around once in twenty four hours . and when it turns around- this is the

beam- it will shine this way . [indicating the part of the ball facing the light] when- wherever it turns around that's where the beam is- on the side

The concept at issue here is the relationship between the sun and the earth and how that accounts for day and night. The two boys were, of course, very familiar with the diurnal change from daylight to night-time and with the role of the sun in providing light. As with all English speakers, they talked in everyday language about the sun moving in relation to the earth, making use of the concept of the sun appearing each morning in the east, rising to a position high in the sky, and descending to set in the west. This way of talking was probably appropriated at a relatively age from conversations in the home, perhaps when planning an outing or watching the sun coloring the clouds as it set. But at some point in their schooling they had “learned” that it is not the sun that moves but rather that the earth moves round the sun and also turns on its axis once in each day-night cycle. For the construction of the sundial, however, the choice of explanatory model was not really important. In fact, the “everyday concept” was probably more helpful. The teacher’s question was, therefore, an interruption to their practical knowing – a test rather than a contribution to their project. In this situation, the students tried to remember what they had been taught, which, for Lionel in particular, was difficult to reconcile with the movement of the shadow on the sundial.

The second example involves somewhat younger children. It comes from a grade four class, in which the students had constructed model cars and run them down a ramp, then tried to make improvements with the aim of enabling their cars to travel further from the bottom of the ramp. One such improvement they had tested was to add weight to their cars. However, contrary to their predictions, this had the effect of reducing the distance traveled. Two possible causes were suggested. The first was that the change of direction caused by the angle between the bottom of the ramp and the floor was more consequential in slowing the cars down when they were heavier. Miguel, an English language learner, who recalled his ride on a rollercoaster, made the following suggestion: Example 4.

Miguel: .. say you started off high - this was gravity - . so . it could- it would be softer if you put a piece of paper right there [pointing to the bottom of the ramp] and taped it and it [the car] goes like that [gesturing a curved trajectory when the car traveled over the paper] . like that [demonstrating on his open journal] . and then it could run away . it's going far . would go far

This suggestion was immediately taken up but, although distances increased on the majority of trials, cars with added weight still traveled a shorter distance on average than without added weight. Another student conjectured that perhaps the cause was the carpeted surface of the floor, and the term “friction” was used in explanation. This led to a proposal to try running the cars outside in the yard, where there was an asphalt surface. Here, results were less conclusive. In the case of most cars, distance traveled was greater than on the carpet. However, for the minority of students who went on to try the effect of adding weight, the results varied considerably.

Back in class, Jesse was keen to explain why his car traveled further on the asphalt with added weight:

Jesse: My theory . like- . well it's not really <a proper theory> but it's like weight- .why weight causes <further on> the asphalt . cos the asphalt has little bumps which- the little bumps make the cars go UP a little bit and that slows them down . but with weight . um it keeps the car um . going to- going THROUGH the bumps

In both these last two extracts, the students were trying to resolve a problem. Using the concept of the relationship between momentum and distance traveled, they confidently expected that adding weight to their cars would make them go further (as did the adults). But having carried out three trials with each car in each condition, the results were conclusive: adding weight did not make their cars go further. They were naturally keen to come up with an explanation that they could put to the test. Miguel's suggestion, prompted by his thinking about the rollercoaster, was based on a conjecture that smooth transitions in direction were important in maintaining momentum and, when tested, his

conjecture proved to be correct. However, it did not resolve the problem raised by the unexpected results with respect to weight.

Jesse, on the other hand, did have a clear result to report and one that confirmed the class's initial prediction about the effect of adding weight. However, what needed to be explained was why adding weight had a different effect on the asphalt than it did on the carpeted classroom floor. Since the different surfaces and the possibility of differing amounts of friction – on the carpet and on the asphalt – were the variables under consideration, he examined the asphalt surface carefully and saw that there were both bumps and little pieces of grit on the surface. Conjecturing that this was perhaps the cause of his car going further with added weight, he constructed an add hoc – but plausible – “theory” of how weight might be an advantage in maintaining momentum on such a surface.

It is notable that neither boy used the technical term “momentum”, although it had been used by the teacher and some students on several occasions in previous lessons. However, it seems clear that each was thinking with the aid of such a concept. Miguel was recalling his smooth ride on the rollercoaster and understood that conservation of momentum was the critical concept for explaining why the car on the rollercoaster could continue over such a long distance and surmount the smaller rises after the first hair-raising descent. Jesse's experience was even more recent but it seems that he had no comparable experience to draw on. However, given the class focus on surface textures and previous discussion of momentum, he constructed an explanation that was obviously convincing to him and also to his teacher.

### **Engagement and Understanding**

In their discussion of different ways of accounting for the occurrence or non-occurrence of conceptual change, Treagust and Duit briefly discuss the influence of the “affective domain” [14], remarking that the influence of students' interests and motivation has had limited attention from CC researchers. Nevertheless, they go on to cite Pintrich et al.'s (1993) review, which shows that several CC researchers have drawn attention to the importance of interest, personal beliefs and social relationships to students' engagement in learning activities.

On theoretical as well as empirical grounds, it seems entirely reasonable to suppose that students' success in understanding and using new concepts will depend to a considerable extent on the manner in which they are challenged and supported in engaging with them and on the felt utility of the concepts in enabling them to make sense of a problem that is of genuine interest to them. Interest, in the sense of caring about what one is doing, is almost a prerequisite for active engagement, for it provides the motivation to struggle with difficult tasks, even when success is not easy to achieve.<sup>7</sup> The desire solely to obtain good grades is much less effective in this respect (Ball and Wells 2006). Feelings concerning self-efficacy also affect the quality of students' engagement (Bandura 1994). In addition, the affective tone of interpersonal relationships can also be a significant influence, particularly when tasks are undertaken jointly with peers.

Affect is clearly important in examples 3 and 4 above. Alon and Lionel were not really interested in the question posed by their teacher, as it did not seem to them to be significantly related to their own goal of making a working sundial. Yet, to some degree, the initial disagreement between them was sufficient to draw Alon in to picking up the ball and, with it, demonstrating his understanding to Lionel in a manner that seemed to emphasize his greater competence. In the second example, by contrast, both Miguel and Jesse were, like most of their classmates, strongly committed to figuring out how to make their cars travel further, and this sense of "ownership" of the problem led each to engage in knowing-in-action to understand the significance of their experiences.. It was also significant for their continuing engagement that their contributions were positively received.

Similar issues arise in some of the interviews quoted by Treagust and Duit, although they are not directly referred to in their discussion of specific extracts. Consider, for example, the following two interviews with students some weeks after a unit on optics in two different grade 10 classes taught by the same teacher. They describe how, in both classes, the teacher had presented the concept of refraction by explaining that the bending occurred because the light slowed down when it entered a glass block and sped up when

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<sup>7</sup> It is important to point out that interest does not have to preexist a challenging problem; it is often the problem itself that generates interest.

it re-emerged. However, in the second – but not the first – class, in order to make the concept easier to grasp, the teacher had also used an analogy, comparing the ray of light to a pair of wheels as they rolled obliquely from a hard to a softer surface. The first interview was with a student from the first (control) class.

Example 5.

Int. Would you like to tell me what happens here to make it [the beam of light] bend?

Jane Because it is going through different densities ... it makes the light bend.

Int. How does the density affect the beam to make it bend?

Jane I'm not sure. Don't know.

Int. Have you got any idea what happens here to make it bend?

Jane The light slows down...

Int. Any idea how that [bending] happens?

Jane It might be or it might not be different densities in there [the glass block].

Using Hewson and Hennessey's (1992) categorization of students' responses as showing whether a concept was intelligible, plausible or fruitful, Treagust and Duit then comment on Jane's responses as follows:

Jane demonstrated that the notion of refraction being related to light changing speed in media with different densities was intelligible to her. However, statements like, "I'm not sure" and "it might or might not be" indicated that she did not necessarily believe that this is how the world actually is and the concept was probably not plausible to her. [30]

By contrast, in the interview with Dana, who "was vague and unenthusiastic during the initial phase of the interview" [32], the interviewer prompted her to consider whether she could think of any helpful analogy.

Example 6.

Int. O.K. Can you think of any simple analogy that would help you explain to

a friend why those pencils appear to be bent?

Dana No. I don't think I'd be able to explain it 'cause I don't know myself.

Int. Right, did Mrs ... use an analogy when she taught you this?

Dana Umm ... She used a car type of thing with wheels when it was changing from a piece of carpet to paper.

Int. And what happened when the wheels went from carpet to paper?

Dana It bent because one wheel got onto the paper before the other one and one is rougher than the other surface.

Int. So what happened to the wheel that got onto the paper first?

Dana It went faster so it turned.

Int. O.K. So one wheel was going faster than the other was it?

What happened when the other wheel got onto the paper too?

Dana Then it just went straight from there.

Int. O.K. So the direction of the wheels changed because the speed changed did it?

Dana Mmm.

Int. Does that fit in, in any way with light?

Dana Yes, because light changes faster in air than it does in water.

Int. Alright, let's come back to your sketch. What will happen when the beam of light hits the surface between the water and the air?

Dana It would probably be bent that way.

Int. Did the wheels help you work that out?

Dana Yes.

Int. Did you initially remember the wheels?

Dana No.

Int. Alright, so when you didn't think about the wheels you had no idea what happened to the ray of light?

Dana Uhhu.

Int. When you think of the wheels, you can work out which way it bends?

Dana Yes.

Treagust and Duit's commentary on this interview includes the following evaluation.

There is evidence in the transcript of Dana making connections between the analogy and the behaviour of light as it passes from one medium to another. This connection was fruitful for her in that after she became dissatisfied with her answer to the first question in the interview she corrected her drawing and then accurately answered the glass block and prism questions...

In addition, Dana's answers to the subsequent beam tracing problems using glass blocks and prisms were among the best of the 39 students interviewed. In contrast, the teacher had placed Dana in the bottom 25% of the class and Dana had failed the Optics unit .. When the analogy was recalled, she became enthusiastic and talkative. The introduction of the analogy led to her becoming dissatisfied with her initial answer to the first question and she confidently changed her vague ideas into a correct response. [34-35]

There are several interesting differences between these two extracts, in addition to Jane's response being categorized as showing that, for her, the concept was only intelligible, while for Dana the concept was intelligible, plausible and fruitful. The first difference is in whether or not, during the actual taught unit, the two students had been given the analogy of the wheels. As a function of the research design, Dana had, but Jane had not. It seems very likely, therefore, that Dana had, potentially, a more complex set of experiences to draw on than did Jane. In other words, she had more relevant memories from which to construct a representation of her understanding in the interview. A second difference is in the different ways in which the two interviews were conducted, in particular the nature of the interpersonal relationship that the interviewer established. With Jane, the interviewer simply asked her to explain the phenomenon of light bending,

as seen when it passed through a glass block that was (presumably) present in the situation. When Jane could only volunteer the idea of different densities being involved, the interviewer simply made a further request for an explanation. In the case of Dana, however, when she initially failed to provide an explanation, the interviewer was much more interactive, prompting Dana to recall the analogy of the wheels and then co-constructing the point of the analogy with her.

As a result of these two differences, I would suggest, the interview was experienced quite differently by the two girls. For Jane, it remained a test-like situation, in which she showed little interest and was not very successful. Certainly the experience did not lead her, at that time, to a more effective understanding of the concept of refraction. For Dana, on the other hand, although the first part of the interview (not quoted) was apparently even less productive than Jane's, the interviewer's prompts enabled her to recall the previous experience with the wheels and, with the interviewer, to construct a "re-knowing" of its significance in clarifying the phenomenon of refraction that she had also observed in class. By offering these prompts when Dana was not able to provide an acceptable answer, the interviewer changed the affective tone of the interview and, by working with her, increased her engagement with the problem.<sup>8</sup>

These differences, and particularly the different nature of the two interviews, strongly suggest that a student's affective state – her interest as well as her self-confidence and comfort in the interview situation – makes a significant contribution to her mode of engagement with a task and thus with the possibility of learning from the experience.

More generally, the difference between the two interviews points up the importance of Vygotsky's insistence on the interdependence of affect and cognition (Mahn and John-Steiner 2002; Immordino-Yang and Damasio 2007). It also exemplifies the affective as well as cognitive import of his metaphor of working in the zone of

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<sup>8</sup> Although the interviews were not intended to provide an opportunity for learning, Treagust and Duit suggest that learning may well have occurred in the case of the interview with Dana (cf. Scardamalia and Bereiter, 1983).

proximal development (zpd). In his view, tests (or interviews) that are impersonal and non-interactive provide a very limited estimate of a person's understanding. In order to find out a child's potential for enhanced understanding, he argued, it is not sufficient to discover the child's actual developmental level, for example, the level of item difficulty that a child can manage on his or her own. A more adequate indication is only to be found, he argued, by discovering what level of difficulty the child can manage with assistance in the form of leading questions, the tester initiating the solution for the child to carry to completion, or the child solving it in collaboration with other children. As he puts it, "what children can do with the assistance of others [is] more indicative of their mental development than what they can do alone" (1978). This certainly seems to be borne out by the experiences of Jane and Dana.

In *Thinking and Speech*, Vygotsky (1987) extended the zpd metaphor by making the connection between assessment and instruction. Briefly, his argument was that instruction should not await development but, rather, should lead it: "The only instruction which is useful in childhood is that which moves ahead of development" (p. 211). However, in order to provide this sort of instruction, it is necessary to discover both the lower and the upper bounds of the child's zone of proximal development so that, while instruction builds on the child's experience, it leads the child beyond her or his current understanding. This sort of formative assessment is thus an integral aspect of instruction, which itself is seen as involving collaboration between the learner and the teacher or peer(s) that involves affective and interpersonal as well as cognitive dimensions.

### **Learning and Teaching the Use of Concepts in School**

In the final section of their paper, Treagust and Duit consider the effectiveness of instruction that is based on a conceptual change approach. Overall, the evidence in favor is equivocal for a variety of reasons, one of which, they suggest, is the pervasive gap between the approach to conceptual change developed by researchers and the teaching practices that prevail in schools, which they report as being largely transmissional in orientation. They do not, however, consider the possibility that the attempt to bring about conceptual change may be, in itself, an inappropriate way of working toward the achievement of the PISA goals of scientific literacy that they quote.

The charge that is made against contemporary teaching is that, by and large, teachers are not familiar with constructivist ideas and that their practice is driven by “considerations about the content in question ... Reflections about students’ perspectives and their role in the learning process play a comparably minor role” [86]. This is probably accurate. However, much of the research discussed by Treagust and Duit is not immune from similar charges, particularly the earlier work, in which efficiency in bringing about conceptual change was the goal, with efficiency defined as “exclusively or predominantly cognitive outcomes of instruction” [79]. Apparently, these researchers, too, were uninfluenced by a constructivist approach and paid little attention to students’ perspectives or to creating the conditions that would optimize their engagement.

However, even the adoption of a constructivist approach may not be sufficient to achieve the PISA goals if the purpose of instruction remains that of changing individual students’ concepts. In the preceding sections of this paper, I have argued that, rather than thinking of students as possessing concepts that need to be changed, it is more appropriate to think of them as learning to use the powerful scientific concepts that have been developed by others, and which form part of the cultural resources that are already available for their appropriation, in tackling problems that they find interesting and relevant. Rather than attempting to teach concepts because they are considered to be important in themselves, a better alternative is to enable students to discover their utility as they try to solve problems that arise from their own inquiries. As Brown, Metz and Campione (1996) emphasize, the learning of scientific concepts requires a context of inquiry.

Drawing on the work of both Piaget and Vygotsky, Brown and colleagues describe the aims for their research with grades five and six “Communities of Learners” as “devising learning environments that enable group participation and dialogic interaction, which support reflection, argumentation and refutation. ... Students operate as researchers who are free to select a topic of inquiry, free to do research on whatever they like within the confines on the targeted topic for their grade” (1996, p.159). This freedom of choice to expand on their own interests is critical in enabling students to feel a sense of ownership and self-direction in their work and this, in turn, fuels their motivation to work at achieving understanding.

Writing about his experience in this class some years later, a former student had this to say:

The freedom, the freedom, was the first part ... in the type of work. It was important ... we learned about DDT and pollution and its effects on a population, poisoning crops ... and nothing else I did in elementary was even close to the level of that project or that work ... the endangered species ... it was really important, and would help, help in the world. (Quoted in (Rutherford and Ash in press)

Like Brown and colleagues, others – classroom teachers as well as university researchers – have discovered that dialogue is at the heart of a community of learners and that nothing generates dialogue as effectively as students having results to report from their own inquiries (e.g. Palincsar, Magnusson et al. 1998; Hume 2001). When inquiries are carried out in collaborating groups, the opportunities for dialogue are further extended, since they occur within the groups as well as in whole class discussions, as students debate plans of action, interpret results and try to relate them to their inquiry questions. Arguing for the value of such discursive strategies, Hatano and Inagaki (1991) proposed:

In the course of discussion, students may be surprised to find out that there exist a number of ideas, plausible though different from their own. In addition, they may be perplexed by being unable to decide which of the alternative ideas is most tenable. The presence of others expressing different ideas is especially advantageous, because it is hard to recognize as plausible those ideas which we merely read or get exposed to passively. More importantly, when asked for clarification of their views or when they are directly disputed, students may become aware of the lack of coordination among the bits of knowledge they possess. (Quoted in Herrenkohl and Guerra, 1998, p. 440)

However, while occurring fairly frequently in small inquiry groups, Hatano and Inagaki's three discourse practices – clarification, disputation and coordinating evidence with theory – have been found less likely to occur spontaneously in whole class

discussion. To attempt to overcome this problem, Herrenkohl and Guerra (1998) carried out a design experiment in which different students in a grade four class were assigned the roles corresponding to these three strategies, which they were to enact, as appropriate, in responding to student groups' reports of their inquiries to the rest of the class. While teacher modeling of these roles was needed initially, by the end of the experiment students were able to manage them without assistance. Although the teacher continued to share the role of checking comprehension, Herrenkohl and Guerra report, "the students were the primary initiators of episodes that coordinated theories and evidence and challenged others' claims" (p. 466). Reviewing these results, they argue that "combining guidance on the social as well as intellectual level proved to be a more effective way to encourage student engagement than providing the cognitive piece alone" (p. 467).

A further advantage of adopting a community of learners/inquiry approach, is the greater opportunity that this provides for "multiple zones of proximal development" (Brown et al., 1996, p.161). When students work collaboratively in groups on their own questions under an umbrella theme chosen by the teacher on the basis of her/his knowledge of the students as well as the requirements of the mandated curriculum, there tends to be greater engagement and a reduced need for the teacher to monitor student activity. As a result, s/he can spend sustained time with individual groups, recognizing their achievements as well as assessing their need for assistance, and providing help with group working practices as needed, as well as asking probing questions, offering suggestions and in other ways assisting them to make progress with their chosen investigations. In these ways, the teacher also models effective forms of collaboration, which, over time are appropriated by the students so that they begin to provide similar assistance to each other. As Galbraith, Van Tassel and Wells (1997) found, this is possible even as early as grade two if students are truly engaged in investigating questions that they themselves have proposed.

Many of these advantages underpin the following extract from a unit on light in the senior class in a K-8 school in a metropolitan city in Canada.<sup>9</sup> Students in this grade eight class have been experimenting with various types of mirrors and lenses and their teacher, Karen Hume, is in the process of reviewing what they understand about reflection and refraction. Karen's purpose is to use this review as the basis for decisions about what further questions they wish to investigate. At this point in the lesson, Sasha remembers somebody having mentioned side mirrors on cars.

Example 7.

- Sasha: What about those mirrors that make the object larger than they appear . like in those car mirrors- or...
- Karen: Good question . that's an excellent question . what is happening there?
- Sasha: I don't know . is there like a lens in front of the glass- or in front of the mirror?  
[unintelligible as many students talk at once]
- Karen: OK . Matt's just made a good point in response to that .  
Matt, you're saying-?
- Matt: It says that objects may be closer than they appear.
- David: Yes
- Karen: But not necessarily larger, right? . OK . so what's happening there?  
Amanda?
- Amanda: There is car things that you stick at the back of your something .  
it makes it all big \*\*. in the back of your-
- Karen: Right, but they're talking about the side mirrors in the car . and it's usually printed in there- objects in this mirror may be closer than they appear, OK? So . what is it that's happening with that? if it's changing the size of the image- is it a mirror- or is it a lens?

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<sup>9</sup> Known as "The Developing Inquiring Communities in Education Project" (DICEP), this project was funded by the Spencer Foundation between 1991 and 2001 (Wells, G., Ed. (2001).

- Simon: Both
- Ian: Maybe . OK . you know how big and little \*\* you can change the angle? maybe it's because of that . and if it's a bit curved . like- maybe it's con- .. what is it? . convex!
- David: Maybe- like the lens is part of the mirror? so like there's a mirror . and on top of the mirror there is a lens . which will magnify it
- Karen: OK . Phil
- Phil: I think it's because- like you know when this way it gets bigger or wider- and this way it gets taller . maybe it bends both ways so it's like rounded . so it like stretches it both ways . so .. or shrinks it both ways....
- Karen: So- your saying it's a convex and concave mirror?
- Phil: No, it's uhm- a convex mirror . except it's like convex this way and convex this way [gesturing]. so- like circular and the object in the same spot . so if you look at it it's like a little bit out- a little bit curved
- Karen: Can you come up with a question about this- or theory about this?
- Omar: Um- you know how “objects in mirrors are closer than they appear”? . could that mean two things though? could that mean that they appear closer than they are in the mirror? [Karen: Right] cos in my mirror it looks smaller than if you just look at them through the cars  
[Several more turns intervene as students offer further suggestions]
- Karen: (Writing on the blackboard as she speaks) Guys this is terrific . you are coming up with some great stuff here . the objects are closer than they appear . OK, what does that mean .. what are the options?

By this stage in the unit, there is a considerable amount of common knowledge about mirrors and lenses, although different groups of students are more expert on some topics than others as a result of the experiments they have already conducted. In this context, Sasha's question about passenger-side wing mirrors generates some contradictory possible explanations of the way in which these “mirrors” function. Since these young people will soon be learning to drive, the question is one of genuine

importance to them – as their teacher recognizes. But rather than telling them the answer, she sees it as a worthwhile issue for further investigation. Her question, “What are the options?” is an implicit invitation for the students to use their understanding of the concepts of concave and convex, reflection and refraction, to solve the problem – as one group then proceeds to do. Furthermore, the movement back and forth between student-chosen problems and discussion of the more abstract general principles, in which specific concepts are related to each other within a system of concepts, builds on Vygotskian ideas about learning scientific concepts; it also follows the findings of research on learning and transfer (Bransford, Brown et al. 2000) or what Beach (1999) calls “consequential transitions.”

### **Conclusion**

In this response to Treagust and Duit’s paper, I have tried to make three main points. The first is that scientific concepts are cultural artifacts (third world objects, in Popper’s terms) that, as components of a system of concepts, have been proposed, revised and improved over many generations by the community of professional scientists in order to increase their understanding and possibilities for action. As human constructs, however, they are not immutable for, at any time, they may be transformed according to the uses to which they are put in different activities. Nevertheless, until superceded, they are, in their different fields of use, the most powerful tools available for the purposes for which they were constructed. Because concepts are culturally produced artifacts, they do not belong to particular individuals (despite attempts to secure intellectual property rights) but are available for all to use, in the processes that occur in Popper’s world 2, as thinking tools for solving problems of a similar or related kind. However, while never becoming individual possessions, concepts can be appropriated in the sense of individuals learning when and how to use them for particular purposes. Nevertheless, because of their abstract, decontextualized nature, they always have to be interpreted or reconstructed according to the particularity of the situations in which they are used.

Second, since scientific concepts are tools developed for particular purposes, they should not be thought of as universally appropriate for all types of problem solving. In many areas of contemporary human activity, such as the law, commerce, or the arts, other

conceptual toolkits are available, which may be of equal or greater utility for solving the problems that arise in those activities. Systems of scientific concepts are of relatively recent origin, having for the most part been constructed in the service of empirical scientific inquiry that dates back only a few hundred years. However, long before the scientific enterprise gathered momentum, all cultures had developed conceptual tools for making sense of the events in their daily lives, which were embodied in the language they used to co-construct their understandings. Many of these ways of thinking are still embedded in everyday ways of talking and, in a wide variety of situations, they continue to be effective for the purposes that they serve. Thus “everyday” ways of conceptualizing can only be considered to be “misconceptions” when viewed from the perspective of those activities, such as scientific investigation and the utilization of the findings of such activity, in which scientific concepts prove to be more powerful.

Third, in learning their community’s language, children everywhere adopt the ways of speaking and thinking that enable them to make sense of the events of everyday life within their culture and, because the conceptual tools provided by their language continue to be effective for such purposes, they take them unquestioningly for granted. Attempting to persuade students to “change” or “replace” the concepts they use through instruction in school is unlikely to be successful unless learners recognize that the proposed alternatives are effective in solving problems that they themselves see as meaningful and significant in relation to their own life concerns.<sup>10</sup> As Vygotsky wrote about the teaching of writing, "teaching should be organized in such a way that reading and writing are necessary for something ... Writing should be incorporated into a task that is relevant and necessary for life" (1978, pp.117-118). Since the learning of writing and of scientific concepts were, in his view, closely related, in that both require conscious awareness and voluntary control, the same injunction seems to apply equally to the latter.

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<sup>10</sup> The reluctance of many adults to use computers provides a good analogy. Being adept at using pencil and paper for making mathematical calculations or for writing letters or other types of text, they do not feel the need to learn to use a different kind of tool, which is less transparent in use.

Acceptance of these arguments about the nature and use of scientific concepts can, I believe, help us to think about better ways to assist learners to understand and use these resources, which are clearly a valuable part of our cultural heritage. In important ways, scientific concepts are like the microscopes, calculators, measuring devices, vacuum pumps, and other material tools that we use to engage in mathematical and scientific activities. Just as these tools can change the way we perform experiments or design and manufacture useful artifacts, so theories and the conceptual systems with which they are constructed can enable us to better understand the nature of the world around us and to plan how to transform parts of it to produce or improve those artifacts, whether the desired outcome is an object in world 1 or in world 3.

Learning to use material tools is most easily achieved when the learning takes place in an activity in which the tool serves a recognizable purpose and assistance is available from more skilled participants in the activity. It is also necessary that the learning be within the learner's zpd. Initially the learner's use of the tool may be awkward and not very effective but, with help and practice, the novice develops expertise in its use comparable to that of the old-timers in the activity (Lave and Wenger 1991). In many cases, an explanation of how the tool functions to achieve the purpose for which it was designed may also facilitate learning how to use it.

The same basic principles apply in learning to use semiotic tools (Collins, Brown and Newman, 1989). Through design experiments such as those discussed in the previous section, considerable progress has been made in discovering how to engage students in this sort of "apprenticeship," in which learning to use scientific concepts is one important aim. Research carried out in collaboration with practicing teachers has also been similarly productive (e.g. van Zee, Iwasyk et al. 2001). In my own work with teachers (Wells 1999; 2001), like Brown and colleagues, and inspired by Dewey (1938) as well as by Vygotsky, we have come to see inquiry as the key element in creating a community of learners. For, it is when students have conducted their own inquiries that they become willing and able to engage in the sort of "progressive discourse" (Bereiter 1994) in which advances are made in both group and individual understanding of the conceptual tools that are useful for making sense of their results. In creating such communities of inquiry, there seem to be two important roles that the teacher needs to take on. The first is that of

selecting meaningful activities that pose challenges that are within the students' zones of proximal development and the second that of collaborating with individuals or groups of students, providing forms of assistance that enable them, as Vygotsky put it, to "rise above themselves," by first mastering those aspects of the task that are beyond their level of independent functioning and then developing conscious awareness and control of them.

Adopting this approach means recognizing that learning – like teaching – involves the whole person in action, feeling, and interpersonal relations as well as in cognition. Learning is also centrally involved in the construction of personal identity. Since "science" is rapidly changing humans' relationship with other people as well as the planet that supports us, it is essential that the learning and teaching of science look beyond the classroom learning of scientific concepts to the uses outside the classroom to which students will put the knowledgeable skills they are mastering. Science cannot be separated from the other activities in which people engage or from the ethical, ecological and political issues that the use of scientific knowledge inevitably raises. Nothing less than this sort of engagement in scientific inquiry, I would suggest, will make possible the achievement of the PISA goals of enabling students "to understand and help to make decisions about the natural world and the changes made to it through human activity."

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