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Out of our minds: a review of sociocultural cognition theory

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Theories of mind are implicitly embedded in educational research. The predominant theory of mind during the latter half of the twentieth century has focused primarily on the individual mind in isolation, context-free problem-solving and mental representations and reasoning, what we refer to as *cognitivism*. Over the last two decades, CS Education researchers have begun to incorporate recent research that extends, elaborates and sometimes challenges cognitivism. These theories, which we refer to collectively as *sociocultural cognition theory*, view minds as cultural products, biologically evolved to be extended by tools, social interaction and embodied interaction in the world. Learning, under this perspective, is viewed as tool-mediated participation in the ongoing practices of cultural communities. In this paper, we pursue three goals. First, we provide a summary of the key principles in sociocultural cognition theory, placing this theory within a historical context with respect to the cognitive theories that it extends and challenges. Second, we integrate across different but related research efforts that all fall under the sociocultural cognition umbrella, using a uniform terminology for describing ideas represented within different discourse communities. And third, we reference a number of canonical sources in sociocultural cognition theory so as to serve as an index into this diverse literature for those wanting to explore further.

Keywords: activity theory; Vygotsky; situated cognition; distributed cognition; legitimate peripheral participation

> Teaching … is inevitably based on teachers' notions about the nature of the learner's mind. (Olson & Bruner, 1996)

Theories of mind in CS Education research

If Olson and Bruner's dictum holds for teaching, it holds equally for educational research. Consider the following research questions: in what way might a clash between the different cultures of CS students and their

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teachers lead to learning difficulties in the CS classroom? What impact do differences in first programming language have on the subsequent programming activity of novice computer programmers? In what way are the sketching and graphing practices used by both student and professional software developers for building software systems related to the social context in which they carry out their work? In asking and carrying out studies to investigate the research questions above, our theories of mind play an important role.

The predominant theory of mind during the latter half of the twentieth century has focused primarily on the individual mind in isolation, problem-solving and context-free mental representations and general reasoning processes, what we refer to as *cognitivism*. As in other educational fields that have adopted a cognitivist perspective, this theoretical grounding has led to significant advances in our understanding of how people think about computation: the generation of programming goals and plans (Soloway, Bonar, & Ehrlich, 1983; Soloway & Ehrlich, 1984), the use of particular cognitive strategies for programme comprehension (Pennington, 1987), the elaboration of the structure of knowledge within the discipline (Robins, 2010), to name just a few. As Kolikant and Ben-Ari state (2008, p. 8), "[i]n two recent reviews of the state of the art in research in CS Education, the dominant theoretical viewpoint on learning was cognitive (Robins, Rountree, & Rountree, 2003; Simon, Fincher, & Lister, 2006)". In our own search of the computing literature, we also found that cognitive approaches continue to be dominant in computing in general and CS Education in particular (see Table 1).

However, over the last two decades, CS Education researchers and practitioners have begun to incorporate recent research that extends, elaborates and sometimes challenges cognitivism (Ben-Ari, 2004; Knobelsdorf, Isohanni, & Tenenberg, 2012; Kolikant & Ben-Ari, 2008). These theories, which we refer to collectively as *sociocultural cognition theory*, view minds as cultural products, biologically evolved to be extended by tools, social interaction and embodied interaction in the world. Learning, under this perspective, is viewed as tool-mediated participation in the ongoing practices of cultural communities.

A perennial challenge for educational researchers is in keeping abreast of new research in cognition. This is made difficult, not only because of the diversity of forums in which this research is described, but because such forums span disciplines and interdisciplines (including anthropology, sociology, psychology and the learning sciences) and hence are described in language that may be unfamiliar to the disciplinary education researcher. For example, of the 34 CS Education-related publications since 2003 indexed by the ACM Digital Library that make reference to "situated cognition" (see Table 1), 16 of these cite only a single reference on this concept: "Situated Cognition and the Culture of Learning", by Brown, Collins, and Duguid (1989). In addition, as new research perspectives emerge, theoretical

Table 1. Number of results from searches in the ACM digital library.

Search terms	Complete DL All years	Complete DL 2003 or later	Only CS Ed-focused All years	Only CS Ed-focused 2003 or later
Cognitive	30,690	24,360	890	658
Cognition	11,896	9381	198	171
Mental model	2196	1922	112	88
Knowledge representation	8384	5301	85	51
Distributed cognition	617	526	7	4
Situated cognition	329	243	36	34
Activity theory	752	622	12	9
Community of practice	789	685	57	56

(All searches carried out on 18 October 2013).
Notes: Each of the search terms above were entered verbatim (including the quote marks) to the search engine for the ACM digital library at http://portal.acm.org/dl.cfm. "Complete DL" indicates that this was the number of items returned without any filters. This includes all ACM publications and many computing-related non-ACM journals and conference proceedings, such as the Journal of Learning Sciences. The "CS Ed-focused" results were obtained by refining the results returned from the respective queries on the complete DL by selecting "Publication Name", and then selecting each and only the publication sources that are concerned primarily with computing education. The complete list of conferences and journals so referenced is: the annual SIGCSE Symposium, SIGCSE Conference on Innovation and Technology in Computer Science Education (ITiCSE), International Computing Education Research Workshop (ICER), Journal of Educational Resources in Computing (JERIC), Transactions on Computing Education (TOCE), SIGCSE Bulletin, Inroads, Koli Calling International Conference on Computing Education, Australasian Conference on Computer Science Education (ACE) and Journal of Computing Science in Colleges (JCSC). We queried about publications within the last decade to address possible concerns that results of queries for all dates would be significantly biased in favour of cognitivism because of its becoming the dominant paradigm several decades before sociocultural cognition theories. If anything, these results show how long some theoretical results take to diffuse, since the great majority of references to cognitivist terms appear within the last decade, despite cognitivism's emergence in the late 1950s.

approaches that share much in common though differ in the details often refer to the same concept by different terms, creating a "babbling equilibrium" (Ostrom, 2005) that only increases the difficulty for the educational researcher interested in understanding and using this theory. For example, the situated cognition of Brown, Collins, and Duguid in 1989 is not identical to that of the authors in the Cambridge Handbook of Situated Cognition of 2009 (Robbins & Aydede, 2009), nor are their conceptions identical among the different authors within the handbook.

Our purpose in this paper is threefold. First, we provide a summary of the key principles in sociocultural cognition theory, placing this theory within a historical context with respect to the cognitive theories that it extends and challenges. Second, we integrate across different but related research efforts that all fall under the sociocultural cognition umbrella. Though drawing from different discourse communities, we use a uniform terminology. And third, we reference a number of canonical sources in sociocultural cognition theory, so that this review can serve as an index into this diverse literature for those wanting to explore further.

Cognitivism

Cognitivism has been the dominant paradigm in psychology since the latter half of the twentieth century. Many date the start of the "cognitive revolution" in psychology to the late 1950s (Miller, 2003), when researchers began to study the *contents* of mind – goals, intentions, plans, mental representations. Under the behaviourist view that predominated psychology throughout much of the early part of the twentieth century, such mentalistic entities were considered unscientific to study because of their subjective nature and the impossibility of directly observing them (Bruner, 1990; Miller, 2003). The cognitivists posit that the mind is like a logic machine, carrying out computation on the contents of memory. As one of the founders of the cognitive sciences comments, these researchers "dream of a unified science that would discover the representational and computational capacities of the human mind" (Miller, 2003). The cognitivist programme is interdisciplinary, with researchers from philosophy, psychology, linguistics, anthropology, computer science and neuroscience significantly contributing (Bruner, 1990; Miller, 2003). With the increasing computational power of the digital computer and the further development of computer science, computers have been extensively used in pursuit of understanding intelligent activity, cognition and learning within this paradigm.

An area of considerable interest has been in investigating the ways in which people mentally represent the world (Bobrow & Collins, 1975; Gentner & Stevens, 1983). These representations have generally been viewed as symbol structures that denote entities and relations in the world (Newell, 1981; Newell & Simon, 1976). These go by such names as *semantic networks* (Woods, 1975), *scripts* (Schank & Abelson, 1977), *plans* (Miller, Galanter, & Pribram, 1960), *frames* (Minsky, 1981) and *schemas* (Rumelhart & Ortony, 1977), though all are generally recognised as being semantically and functionally equivalent to statements in first-order logic (Hayes, 1979). Knowledge as represented in the mind is viewed as context free, allowing for formal rules of inference to be used to generate new understandings inferred from the symbol structures. And it is the abstract and context-free nature of knowledge that allows researchers in this tradition to treat different structures for encoding knowledge (such as the nodes and links of a semantic network, the slots and slot fillers of a frame, or the sentences in logic) as equivalent. Prior to action in the world, a cognitive agent (whether human or artificial) is hypothesised to think through the consequences of action purely through syntactic operations on the mental representation. The thinking agent thus generates counterfactual statements about possible future states of affairs (if I were to do X then Y would occur) so as to construct plans of action to bring about desired world states. Viewing minds as symbolic machines that carry out inference procedures on symbolic representations leads to a particular view of learning: learning is the acquisition, change and application of symbol structures that denote knowledge about the world, such as scripts, plans and schemas.

Viewing minds as similar to computers finds its fullest embodiment in research in artificial intelligence (AI). Methodologically, researchers take hypotheses about the structure and contents of representations in human minds and realise them as data structures in computers. Similarly, human-thinking strategies can be programmed on a computer to operate on the mental representations stored in the computer's memory. Theories of mind can thus be tested through the development of artificial cognitive agents. What has been termed *strong* AI views thinking (whether of biological or silicon-based agents) purely as symbol manipulation, while *weak* AI takes "computer models as being useful in studying the mind in the same way they are useful in studying the weather, economics, or molecular biology" (Searle, 1990).

The unit of analysis for most cognitivist research is the individual mind, and the key questions involve how minds represent the world, how inferences upon such representations can support (subsequent) action in the world, and how agents acquire knowledge. Empirical research typically involves studying human-problem-solving performance (such as playing chess), often using think-aloud protocols (Ericsson & Simon, 1993) in order to make hypotheses about representation and inference. Alternatively or in addition, many researchers build computer programmes based on such representational and inferential models to carry out these actions (Chi, Glaser, & Rees, 1982).

Critiques of cognitivism

Despite its dominance in psychology and education during the latter half of the twentieth century, there were three main critiques of cognitivism that began to emerge during the 1970s and 1980s: from cultural and developmental psychologists, from researchers influenced by Vygotsky's research that began to appear in English in the 1970s, and from critics of the "strong" AI programme. We discuss each in turn.

Critiques of cognitivism were first voiced by several cultural and developmental psychologists who studied mental activity and learning across different cultural contexts. By administering standard psychological tests to different cultural groups in different parts of the world, these researchers obtained evidence that the developmental sequence of cognitive performance that Piaget (1964) and others claimed is universal, instead varies across culture, reflecting the aims, values, resources and practices of the cultures in which children are raised (see Rogoff (2003) for a summary). These researchers also saw how cultural-environmental factors, such as the way language is used in the home and community, differences in child-rearing practices, and the presence or absence of western-style schooling has a significant effect on cognitive activity across a range of tasks. "The field moved more generally beyond the assumption of generality in cognitive development … showing that not everyone went through the same stages and that performance shifted greatly with familiarity of materials, concepts, and activities" (Rogoff, 2003). They discovered (among other things), that only those adults who had western-style schooling performed taxonomic classification of objects (putting animals in one group, food items in another, and implements in another (p. 242)) while those from other communities who had not had western-style schooling classified objects based on "*functional groups*, such as putting a hoe with a potato because a hoe is used to dig up a potato" (p. 242, emphasis in original). From this perspective, in contrast to cognitivism, the mind appears to be much less of a general-purpose computer operating on context-free representations and much more a product of culturally specific forms of activity.

At about this time, the research and thinking of Vygotsky and his students were beginning to be translated into English from their original Russian (Vygotsky, 1962, 1978). This made available to a wide audience of western psychologists a coherent and well-developed body of thought that viewed *mind as culturally constituted*. Mind, Vygotsky claimed, comes into being through goal-directed activity using culturally evolved tools in interaction with others. His research inspired a number of these psychologists (and psychologically oriented anthropologists) to undertake their own studies on cognition and learning, some of which compared the kind of abstract, symbolic thinking characteristic of formal western schooling to "everyday cognition" as embedded in activities such as shopping (Lave, 1988), dieting (Lave, 1988) and dairy delivery (Scribner, 1999) (see Rogoff and Lave (1999) for a wider variety of such studies). What these researchers found was that people undertaking goal-directed activity in everyday settings often used the material and social resources available to them to frame and solve problems, rather than doing mentalistic symbol manipulation on abstract problem representations. These researchers thus began to critique the assumptions and methodology embedded in the cognitivist conceptual framework (see Lave (1988) for a particularly strident critique).

Finally, a third set of critiques began to be levelled at the cognitivist worldview embedded within the "strong" AI programme of research. As much as anything, the dreams of achieving human-like performance by computers as active agents in the world according to the cognitivist principles was failing for all but chess, toy worlds or other highly constrained settings. In addition, there were several empirical studies of human performance that provided evidence that people were using the contingent resources available to hand rather than abstract symbolic representations to carry out real-world activity, e.g. in solving problems that "just plain folks" (to use Lave's term (1988)) have with using photocopiers (Suchman, 1987), or the way in which people use the contingent resources available in physical space to carry out cooking, assembly and packing tasks (Kirsh, 1995). This critique of strong AI crystallised around the notion that human-like cognition requires a physical body rich in sensors embedded in real-world settings replete with material resources and other people (Dreyfus, 1972; Robbins & Aydede, 2008; Winograd & Flores, 1984).

Thus, all three critiques – from comparative studies of people across cultural groups, from the writings of Vygotsky and his students, and from critiques of the strong AI programme – served as a basis for the development of sociocultural cognition theory, which articulated the way in which minds, tools, culture and world are inextricably bound. In the next section, we describe some of the key theoretical stances of these researchers.

In telling a historical story, we do not mean to convey that sociocultural cognition theory has supplanted cognitivism or that there is no continuing dialogue and debate among scholars in the cognitive and learning sciences related to these (and emerging) theories of mind. For example, *Educational Researcher* featured a debate between proponents of these theories in the late 1990s (Anderson, Reder, & Simon, 1996, 1997; Greeno, 1997), including various attempts at reconciliation (Cobb & Bowers, 1999; Sfard, 1998). More recently, review papers by Barsalou (2008) and Wilson (2002) discuss recent research in cognition and implications for the points of conflict between sociocultural cognition theory and cognitivism, demonstrating that the theoretical landscape related to cognition is far from settled.

Sociocultural cognition theory

The research that we will describe is from a family of closely related theories, variously named *situated cognition* (Robbins & Aydede, 2009), *distributed cognition* (Salomon, 1993), *socially shared cognition* (Resnick, Levine, & Teasley, 1991), *sociocultural learning* (Rogoff, 2003), *cultural psychology* (Cole, 1998), *distributed intelligence* (Pea, 1993), *cultural learning* (Tomasello, Kruger, & Ratner, 1993), *situated learning* (Lave & Wenger, 1991), *embodied cognition* (Wilson, 2002), *activity theory* (Kaptelinin & Nardi, 2006) and *cultural historical activity theory* (Roth & Lee, 2007). Although there are differences among them, they all branch from a common root, sharing many of the same principles. We will use the term *sociocultural cognition theory* to refer to this family of theories, recognising that in doing so we are glossing some of the differences. Sociocultural cognition theory has its roots in Russian psychology of the 1920s, starting with Lev Vygotsky. Its period of most intense activity was in the 1980s and 1990s, with the majority of research carried out by researchers from the USA and Scandinavia. By combining results that have accumulated from closely related approaches, our exposition below is as much synthetic as it is descriptive. Most of the source texts that we draw from are those listed just above, and each serves as an important source for a deeper exposition of members from this family of ideas.

In this section, we summarise what we consider to be the four key principles of sociocultural cognition theory. The first principle states that activity is mediated by cultural tools, highlighting the important role that physical and symbolic artefacts play in cognition. The second principle, that cognition involves looping between brain, body and world, acknowledges the tight coupling between perception, tool-mediated action in the world and thinking. The third principle, that cognition is distributed across people and tools, emphasises that public and perceivable activity and externalised tools enable the coordination of human activity to carry out tasks that would be difficult if not impossible for an individual to carry out unaided by tools and other people. And the fourth principle, that learning is the transformation of participation in ongoing sociocultural practices, highlights the cultural development and reproduction of tool-mediated practices that are carried out among members of cultural communities within authentic settings.

Principle 1: activity is mediated by cultural tools

Sociocultural cognition theory draws from Vygotsky the central idea that virtually all human cognition and activity is mediated by tools (Vygotsky, 1978; Wertsch, 1988). The term *tool* denotes not only material objects used to affect the material world, such as pencils, hammers, automobiles and steam shovels. It also denotes symbolic objects used to affect the mental world of the self and others, such as "language; various systems for counting; mnemonic techniques; algebraic symbol systems; works of art; writing; schemes, diagrams, maps, and mechanical drawings" and similar (Vygotsky, 1981). *Internalisation* refers to the process by which these symbolic objects are created in the mind of an individual from his or her activities. In cognitivism, symbolic objects in the mind, (i.e. *mental representations*) are taken to be context free. However, within sociocultural cognition theory, *how* a person internalises some aspect of the world depends on the tools used in learning.

> A fundamental assumption in a sociocultural understanding of human learning is precisely this: learning is always learning to do something with cultural tools (be they intellectual and/or theoretical). This has the important implication that when understanding learning we have to consider that the unit that we are studying is people in action using tools of some kind (see Wertsch, 1991, 1998; Säljö, 1996). The learning is not only inside the person, but in his or her ability to use a particular set of tools in productive ways and for particular purposes. (Saljö, 1999)

There is considerable empirical support for the close relationship between mediation and internalization in research studies in a number of different domains. In one study, Sherin (2001) investigated how different representational systems used in physics instruction – computer programmes versus algebraic notation – affect internalisation and cognition of the students who employed one versus the other. In this study that Sherin reports, five pairs of students each were assigned to one of these two representational systems, and were video recorded while engaged in problem-solving tasks. The programming pairs were asked to develop simulations of physical phenomena, such as "make a realistic simulation of the motion of a ball that is dropped from someone's hand" (p. 24). The algebra pairs were given textbook problems and asked to solve them at the whiteboard, such as "A mass hangs from a spring attached to the ceiling. How does the equilibrium position of the mass depend upon the spring constant, *k*, and the mass, *m*" (p. 13). All pairs were from the third semester of university physics, all of them having been taught using algebra-based physics in the first two semesters. Sherin's main theoretical result is that there were considerable differences in the kinds of understanding that the students expressed from each of the different groups. "Algebra physics trains students to seek out equilibria in the world. Programming encourages students to look for time-varying phenomena, and supports certain types of causal explanations, as well as the segmenting of the world into processes" (p. 54). The implication is that different representations entrain minds differently, provide different "cognitive affordances".

In a set of studies related to mathematical problem-solving by elementary school children (Nunes, 1997), Nunes reports on the different processes and performance in solving area-calculation problems when students used small bricks as opposed to rulers as cognitive mediators. The rulers provide a linear measure of distance (i.e. in one dimension), while the bricks provide units of area (i.e. in two dimensions). In problems involving the measurement of area, using rulers also require the use of a formula that encapsulates a general relationship between each dimension and the area that they circumscribe. Using bricks, on the other hand, requires only counting the number of bricks that are necessary to "cover" the area in question.

> This series of studies indicates that the system of signs that the children were offered in the learning phase influenced the reasoning principles that they used in organizing the problem solution. The structuring of the children's action was not independent from the tool they had at their disposal in the problem-solving situation. Consequently, the very reasoning principles developed were structured by the system of representation used. (p. 308)

Another research study powerfully exemplifies how different mediational means require considerably different internal mental representations for an actor trying to accomplish a task. Hutchins performed extensive ethnographic research on a 17,000 tonne (15.5 M kg), ocean-going US Navy ship (1993, 1995) and compared the navigation activities there to those of Micronesian navigators in small long rigger canoes (Hutchins, 1983). Navigating the large Navy ship is mediated by a considerable number of technologies, including wristwatch, telescope, alidade (a sighting device) and magnetic compass. The Micronesian navigator, on the other hand, often takes solo open-ocean voyages of several hundred miles several days from landfall without the benefit of these technologies, relying solely on direct sensory perception (of waves, water and stars) in real time. The performance of Micronesian navigators is remarkably reliable: "Of the thousands of voyages made in the memory of living navigators, only a few have ended in the loss of a canoe" (p. X). As evidence of the impact of tool mediation on resulting mental representations, Hutchins comments about the Micronesians "[t]hese navigators are … able to tack upwind to an unseen target keeping mental track of its changing bearing, something that is simply impossible for a Western navigator without instruments" (1983, p. 192). And of the Navy midshipmen Hutchins states:

> It is difficult to overestimate the importance of the development and use of external representational media in this task. The contrast with navigation in illiterate societies where it is carried out without the aid of external representations is striking. The task and its computational properties are determined in large part by the structure of the tools with which the navigators work. (1993, p. 43)

He concludes that "navigation [is] a system of interactions among media both inside and outside the individual" (1995, p. xvii).

Principle 2: cognition involves looping between brain, body and world

Clark challenges the cognitivist view that mind is internal to an individual, suggesting that mind necessarily – biologically – extends into the world.

> [W]e are in the grip of a simple prejudice: the prejudice that whatever matters about MY mind must depend solely on what goes on inside my own biological skin-bag, inside the ancient fortress of skin and skull. But this fortress was meant to be breached … [O]urs are chameleon minds, factory-primed to merge with what they find and what they themselves create. (Clark, 2001)

When ideas are made manifest in the outer world (i.e. "what they themselves create"), this is often referred to as *externalisation* of thought. Externalisation is the dual of internalisation, and both are tightly linked and co-constituting. Internalised ideas can be externalised (such as in a map, a drawing, an utterance, and a technical tool) and become part of the environment which the person can use for subsequent activity, which, when combined with an individual's embodied perceptual system allows for changes to a person's internalisations. Hence, the interaction between internalisations and externalisations that is enabled by real-time perception and action can be thought of as a "criss-cross [of] brain, body, and world" (Clark, 2008, p. 281), or "cognitive looping". Schön (1983) describes this looping as engagement in a conversation with the world, where the world "talks back", so that thinking is dialogic in form. Thus, under this view, the act of bringing thoughts into material form, such as expressing software designs in sketches and models, is not merely to make visible one's "mental representations", but is itself constitutive of and essential to cognitive activity.

There is considerable empirical support for this interactive, cognitive looping in studies of artists (Kavakli, Scrivener, & Ball, 1998; Van Leeuwen, Verstijnen, & Hekkert, 1999; Verstijnen et al., 1998), architects (Bilda, Gero, & Purcell, 2006; Goldschmidt, 1991) and designers (Kavakli & Gero, 2002). For instance, Clark (2001, p. 19) describes an empirical study by Van Leeuwen, Vertijnen, and Hekkert on the interaction between artist and artefact in the act of creation. This study inquires into the role that sketching plays in the creation of a piece of abstract art. What the researchers find is that "human thought is constrained, in mental imagery, in some very specific ways in which it is *not* constrained during on-line perception … Instead, the iterated process of externalizing and re-perceiving is integral to the process of artistic cognition itself".

In a review of empirical research on the role of sketches and drawings in a wide variety of design disciplines, Purcell and Gero (1998, p. 397) underscore the perceptual-cognitive looping that externalised representations enable the designer to engage in. They particularly underscore the *reinterpretation* that is afforded by the externalisation of ideas in a perceivable form. In this same review, the authors examine the empirical record on the use of diagrams by physical and social scientists, concluding that a similar perceptual-cognitive looping is at play by practitioners in these disciplines (1998, pp. 402–403).

> Is the use of diagrams in solving problems in physics, economics and biology the same as the use of drawings in the design disciplines? … Perhaps the most consistent finding in the design area is that drawings are associated with reinterpretation or the emergence of new ways of seeing the drawing. This is also a fundamental aspect of the use of diagrams [in the sciences]. Relevant features are noticed or recognized from a diagram once it is drawn – a process very similar to the reinterpretation of drawings in design. The consequences of reinterpretations appear to be the same for diagrams and drawings. In both cases, reinterpretation cues access to other relevant knowledge and allows inferences to be made.

All of these studies support the assertion that externalising thought in a perceivable form (a sketch, a model, a prototype, an outline and a draft) is therefore much more than simple cognitive offloading. This is because these externalised artefacts are available to the perceptual system, thus giving rise to iterated perceptual-cognitive loops that are not possible with purely (internal) mental representations.

Principle 3: cognition is distributed across people and tools

Externalisations also become available not only to the people who generate them, but publicly, to other agents, and in this way (and through tool-mediated coordinated social activity in general), cognition can be thought of as being "distributed across" tools and other people. What we have been calling *externalised representations* are particularly important for their role in this coordinated cognitive activity, and are what Roth and McGinn (1998) refer to as *inscriptions.* They deliberately appropriate this term from the sociology of science (e.g. Latour (1987)) to distinguish between mental, internal representations and those that are external and publicly perceivable. Pea elaborates on the nature of inscriptions, highlighting their social nature.

> I use the term "inscriptional systems" rather than "symbol systems" or "representational systems" for two reasons. First, I want to stress the external, in-the-world status, which allows for construction, review, deconstruction and the emergence of completed structures of inscriptions that have little relation to their patterns of temporal development (Latour & Woolgar, 1986; Lynch & Woolgar, 1990). Second, both "symbol" and "representation" have taken on the cognitive sciences interpretation of *mental* representation, deemphasizing the sociohistorical fact that many of the kinds of notations that are considered to be among the languages of "thought" – such as mathematical language, written language and scientific symbols – began their existence ontogenetically as external inscriptions whose conventions for construction, interpretation and use in activities had to be acquired in cultural activities. (Pea, 1993, p. 62)

An example of the key role of inscriptions for coordinating human activity is Hutchins's study concerning the navigation of ocean-going vessels mentioned earlier (Hutchins, 1993). In restricted waterways, the navigation of a ship requires precise coordination of the actions of six individuals: two bearing takers, a bearing timer-recorder, a plotter, a keeper of the deck log and the fathometer operator (1993). The *nautical chart* is the central inscription used in carrying out the joint navigational activity of the ship. The chart is a large drawing that represents "the large-scale space surrounding the ship" (p. 40), visible to many members of the navigational team on the chart table. From this chart, lines are drawn from the landmarks on shore from which bearings are taken to determine the ship's present position, and an additional line is drawn in the direction of travel indicating future position at different points in time. The chart is thus essential both for coordinating human activity, for it is where all of the measurements of the different operators coalesce, and carrying out the computational activity associated with "fixing the position". This externalised representation is thus both "out of the head" *and* public, enabling the navigation team within the "horizon of observation" to function intelligently and jointly beyond what any one of them could accomplish individually. Such representational tools "came to embody kinds of knowledge that would be exceedingly difficult to represent mentally" (Hutchins, 1995), i.e. within the mind of any single individual.

Such visible, public representations often serve as crucial elements in complex social activity in a variety of domains. For example, Gawande (2009) describes the use of inscriptions in the form of written checklists for coordinating complex and high-risk activity in surgery, building construction and flying airplanes. Tribble (2005) describes the way in which a particular kind of inscription called a *plot* served as a form of distributed cognition among companies of theatre performers in England during the sixteenth century, necessitated by the demands of performing "a staggering number of plays" (pp. 135, 136). What these examples demonstrate is that there are deliberately designed arrangements of people, objects, tools and representations that influence the mental representations and actions of each individual and the group as a whole. As Hutchins states, we live in a world that can best be characterised as "an ecology of thinking in which human cognition interacts with an environment rich in organizing resources" (Hutchins, 1995).

Principle 4: learning is the transformation of participation in ongoing sociocultural practices

Although, both newcomers and experienced tool users might take for granted their reliance on tools for activity, these tools are not simply found in nature. Rather, they are purposely built by cultural predecessors to exploit the expertise that these predecessors developed while carrying out goal-directed activity in the world. Co-evolving with tools, people have developed tool-mediated *practices*, i.e. "embodied … mediated arrays of human activity centrally organized around shared practical understanding" (Schatzki, 2001).

This focus on practice is a recent borrowing in educational theory from its use in sociology and anthropology.

> Theories of practice (e.g. Bourdieu, 1990; Giddens, 1984; Reckwitz, 2002; Schatzki et al., 2001; Shove & Pantzar, 2005; Warde, 2005) draw on the attention paid in anthropology and sociology to what people do in their embodied, often mundane, situated interactions with other people and with things. Practice theories shift the unit of analysis away from a micro level (individuals) or a macro one (organizations or groups and their norms) to an

indeterminate level at a nexus of minds, bodies, objects, discourses, knowledge, structures/processes and agency, that together constitute practices which are carried by individuals (Reckwitz 2002). (Kimbell, 2012)

Drawing from ethnographic studies of a variety of cultural communities, some educational theorists within the sociocultural tradition, most notably Lave (Lave, 1988, 2011; Lave & Wenger, 1991), Brown (Brown & Duguid, 1991; Collins, Brown, & Holum, 1991), and Rogoff (Rogoff, 2003; Rogoff, Paradise, Arauz, Correa-Chavez, & Angelillo, 2003), believe that learning a large range of practices results from culturally specific forms of interaction over extended periods of time in authentic settings where newcomers to a practice interact with practitioners with more expertise. Collins (2001a) summarises this view in stating that "mastery of a practice cannot be gained from books or other inanimate sources, but can sometimes, though not always, be gained by prolonged social interaction with members of the culture that embeds the practice" (p. 107). Hence, the fourth principle is that learning can be viewed as "transformation of people's participation in ongoing sociocultural activities [i.e. practices]" (Rogoff, 2003). In moving from a cognitivist to a sociocultural perspective, the very concept of what it means to learn is thus altered. Whereas knowledge-in-the-head is all important to the cognitivist, participation-in-ongoing-activity is all important to the socioculturalist.

Participation by newcomers does not simply mechanically reproduce existing social forms, but also transforms existing practices in the process. For example, in a set of detailed case studies, Orlikowski (2000) documents how groups of software users did not simply take technological tools as static and proscribed, but reshaped the tools' functions and uses while they learned to use them through the ongoing interactions with the technology and one another as a "community of users", what she calls *technologies-in-practice.*

The practices within scientific communities in particular have not escaped the sociological and ethnographic gaze. From decades of studying a variety of such communities, Collins emphasises that although science is centrally concerned with the creation of knowledge that is explicit, the *practice* of science – the development and use of instrumentation, the methods of inquiry, the way in which research designs and results are linked to a conceptual framework, forms of reporting – crucially relies on *tacit* knowledge. "Tacit knowledge has been shown to have an influence in, among other things, laser-building, the development of nuclear weapons, biological procedures, and veterinary surgery" (Collins, 2001b). Collins defines tacit knowledge as "knowledge or abilities that can be passed between scientists by personal contact but cannot be, or have not been, set out or passed on in formulae, diagrams, or verbal descriptions and instructions for action" (Collins, 2001b, p. 72).

In his study of experimental scientists who use laser interferometry, Collins (2001b) suggests that there are four reasons why personal contact is required in order for one practitioner to learn tacit knowledge from another: (1) *mismatched salience*: there is a mismatch of internalised notions of salience between learner and expert in terms of the key variables of interest out of the indefinite number presented in the world, (2) *ostensive knowledge*: some knowledge requires co-presence and "direct pointing, or demonstrating, or feeling" as events unfold in the world, (3) *unrecognised knowledge*: the expert might carry out a practice without being aware that aspects of the practice are important in order for it to have its desired effect and (4) *uncognisable knowledge*: the expert might be unable to consciously and linguistically access some aspect of their knowledge. What he demonstrates in his empirical studies is that some knowledge, even among scientists, requires face-to-face interaction to learn.

Seeing the practice carried out by experts using the tools that make the practice possible, and using language to talk about the practice while it is carried out in context, allows novices to understand how particular forms of tool-mediated action are linked to particular effects in the world and to the hierarchical goals of the individuals and community engaged in the practice (Lave, 2011; Lave & Wenger, 1991; Tomasello, Carpenter, Call, Behne, & Moll, 2005). In addition, it allows novices to compare their efforts and the associated effects with the performance and production of experts. And novice engagement in the community's practices under the watchful eye of those more experienced enables experts to provide critical feedback and correction (Rogoff, 2003). As a result, over time, novices are able to appropriate and reproduce the community's practices as they gain increasing amounts of expertise, moving from the periphery of the community of practice to more central roles.

Lave and Wenger report on research that describes such social processes of learning in becoming a practitioner within a range of different communities, including Liberian tailors, Zacatecan midwives and members of Alcoholics Anonymous, a process they call *legitimate peripheral participation* (Lave & Wenger, 1991). In essence, these researchers provide empirical support for the fact that learning occurs when people participate in the ongoing practices of a cultural community.

To summarise, the fourth principle provides a different understanding for learning than that of cognitivism, which is primarily concerned with the acquisition of rule-based, context-free knowledge structures and the generalised procedures that operate on them. By contrast, most sociocultural theorists hold that learning is concerned with participation in the tool-mediated practices that cultural groups use for achieving valued goals within authentic settings. Tools and practices become part of the cultural inheritance that one generation provides to the next, co-evolving over time. Due to the complexity of many of these practices and their tacit nature, new members are incorporated into practice communities through co-participation with experts, thereby reproducing the community and its associated practices.

Discussion

We return to the research questions with which we started, and examine them in light of the review of sociocultural cognition just presented. In doing so, we do not claim that these questions are central to the CS enterprise. Rather, they are exemplary questions from which we can explore how a sociocultural perspective can be integrated into empirical research studies, referencing recent research in CS, mathematics and science education that can be used for guidance.

> In what way might a clash between the different cultures of CS students and their teachers lead to learning difficulties in the CS classroom?

This question was explored by Kolikant and Ben-Ari (2008), using theory that integrates across cognitivist and sociocultural approaches in a manner suggested by Sfard (1998). The authors use the sociocultural perspective in recognising that many students bring their own cultural practices and beliefs about computing into the classroom, many of which are from a software-use perspective. At the same time, many teachers have been enculturated into a community with professional practices and beliefs informed by a formal-analytic perspective. The researchers explored the consequences of these different cultural orientations on learning in a course for high-school students on concurrent and distributed computing. They used a variety of data sources in exploring their research question, including "tests, videotapes of lab sessions, observations, and interviews" (p. 9). The researchers triangulated across their data sources, including the classification of paired student activity in problem-solving that related correctness of answers to false positives and unexplained negatives in their solution rationales, and the explanations that the students and teachers made public to one another in classroom discussion. After considering alternative hypotheses, they conclude that culture clash explains the pattern of behaviour they observed. Students rejected the legitimacy of the teacher's cultural perspective (especially with respect to formal conceptions of correctness), and conversely the teacher rejected the legitimacy of the students' user-based conceptions. Taking these results into account, the researchers then designed an intervention that exploited familiar cultural language for the students while at the same time bridged to the language and formalisms of the professional culture, creating what they call a *fertile zone of cultural encounter.* They conclude:

> [t]he encounter zone is designed to look familiar to the student, thus inviting legitimacy; at the same time, the intervention enables the student to perceive

> that the user perspective is limited and that the professional perspective is productive and accessible, thus facilitating crossing the bridge. (p. 28)

These researchers thus used a sociocultural perspective to interpret the patterns of behaviour that they observed, and used these results as the basis for instructional design that had the effect of changing the discourse between students and teacher when implemented so as to bridge the cultural gap.

> What impact do differences in first programming language have on the subsequent programming activity of novice computer programmers?

This is a perennial question among CS educators, sometimes referred to as the *language wars* (Stefik & Siebert, 2013). The question itself embeds a sociocultural perspective in suggesting that language impacts underlying cognitive processes so that certain ways of thinking and acting with computation are more likely with one language (or paradigm) than another.

Borrowing from research in science education, the results of Sherin (2001) related to physics learning using algebra versus programming and the results by Nunes (1997) on mathematics learning using rulers versus bricks (both described above) provide evidence that the symbolic tools with which people learn can impact the ways in which they conceptualise, talk about and operate on the objects in the learned domain. But finding out if this is the case with programming languages requires investigating not simply what students know in a general sense, but rather comparing how students think, talk and act on the domain objects when mediated by these different programming languages. A recent paper by Stefik and Siebert (2013) takes such a comparative approach, investigating the question "[c]an novices using programming languages for the first time write simple computer programs more accurately using alternative programming languages?" The researchers were led to this research from their previous studies in developing tools for blind and visually impaired students learning to programme, where they noted that there were differences in the readability of different programming languages when using a screen reader (Stefik, Hundhausen, & Patterson, 2011). Their experimental study design for non-visually impaired students involves measuring syntax error rates by students assigned to programme using one of the programming languages Ruby, Java, Perl, Python, Quorum and Randomo. Quorum is a programming language developed by the authors for the purpose of making it "easy to understand and use" (The Quorum Programming Language, n.d.), and Randomo is a programming language developed by the authors as a "dummy treatment" where the keywords were chosen randomly from ASCII. The research subjects were students who had never programmed prior to the experiment. The study results indicate that for first-time programmers, syntax matters in terms of programming accuracy, with programmers using

Ruby, Python and Quorum scoring statistically significantly higher than those using Randomo, and programmers using Java and Perl scoring significantly lower.

Given the complexity of issues involved in comparing the ways in which programming language might mediate cognition, the methods that Sherin and Nunes used to investigate similar issues might be transferred to CS Education studies to yield additional insights. For example, Sherin undertook his studies by randomly assigning pairs of students to one of two conditions, algebra-based and programming-based. The algebra-based students worked in pairs at a whiteboard, while programming-based students pair programmed. Under both conditions, Sherin recorded pairwise interactions with a video camera, occasionally interrupting to ask the students questions. The advantage of having pairs is that it provides a "natural" think aloud, since students have to make their thinking visible to one another in order to collaborate. Sherin analysed the video recordings by focusing on those times when students used particular expressions where students audibly interpreted mathematical expressions, and when they constructed expressions to try to express what they had already stated in English. As reported above, the results indicate considerable differences in conceptions of physics between the algebra-based and programming-based students. Sherin thus uses sociocultural theory to structure the method so that language use-in-practice is closely observed and analysed.

> In what way are the sketching and graphing practices used by both student and professional software developers for building software systems related to the social context in which they carry out their work?

For software developers, externalising an envisioned software system using representations that abstract away from the details of programme code is an important activity (Booch, 2011; Cherubini, Venolia, DeLine, & Ko, 2007), particularly during the conceptual design phase of software development (Baker, van der Hoek, Ossher, & Petre, 2012; Dekel & Herbsleb, 2007; Petre, van der Hoek, & Baker, 2010). Although there have been studies analysing the design inscriptions that students generate (Eckerdal, McCartney, Mostrom, Ratcliffe, & Zander, 2006; Tenenberg et al., 2005), there are as yet no studies in CS Education that examine students' inscriptional *practices* and the relationship of such practices to the instructional context in which students were taught.

Undertaking such a research project might be informed by a similar study, in which Roth and McGinn (1998) explored the relationship between inscriptional practice and instruction for students learning science. They describe a study in which the inscriptional practices of three distinct populations, eighth-grade students, university graduates (with either BS or MS degrees) and professional scientists, were investigated, along with the social context in which they each worked and learned. Each population was presented with a real-world problem that presented a map with several measurement pairs. The research respondents were asked to describe what relationship there is between the variables represented by the measurement pairs and to provide a convincing argument for their answer. The researchers had the surprising result that over twice as many (48% vs. 19%) eighth-grade students in comparison with university graduates "drew on sophisticated mathematical methods including graphing and correlation techniques" (p. 48), where such methods were similar to those of professional scientists. The surprise disappears, however, when the instructional context for each group is made visible. The authors note first that the university students "did not engage in graphing practices in the way the practicing scientists did" (p. 48) having had a "standard fare of science teaching" (1997, p. 94). By contrast, this specific group of eighth-grade students were taught in an inquiry fashion, whereby they:

> constructed increasingly convincing inscriptions of their data and thereby engaged in elaborate transformations which produced cascades of inscriptions … In addition, they engaged in a range of scientific practices that linked observations and inscriptions in a continuous stream of practices. (p. 48)

Thus, the inscriptional practices of the professional scientific community were made an explicit aspect of the instructional design for the eighth-grade students, and this same sociocultural framing was used as an analytic basis for accounting for the differences in performance between the eighth graders and the university graduates. Sociocultural cognition theory thus serves as the basis of an instructional design as well as the framework for interpreting the study results. In taking a practice perspective, the authors argue:

> [t]his perspective views graphing as practice; it focuses our attention on students' competence and rhetorical purposes, and on the affordances of graphs to collective sense-making … Furthermore, the practice perspective focuses on participation in meaningful practice and experience; lack of competence is then explained in terms of experience and degree of participation rather than exclusively in terms of cognitive ability. (1997, p. 92)

Comparing across the studies referenced above, sociocultural cognition theory is used in a variety of ways in shaping empirical research. In all of the referenced studies, the theory is visible in the research questions themselves, whether the study concerns the way that students and teachers might carry different cultural beliefs into the classroom, how symbol systems mediate thought, or the relationship between inscriptional practices and the situated context of learning. Sociocultural cognition theory is also used as a basis for designing the study, as in the paired problem-solving of Sherin and Nunes.

The theory can be used as well as an analytic lens in accounting for the patterns of data that are observed, as in the study by Kolikant and Ben-Ari, and that of Roth and McGinn. And finally, this theory can be used as the basis for instructional design, as is the case in both Kolikant and Ben-Ari, and Roth and McGinn.

Conclusion

In this review paper, we have described a set of key principles from sociocultural cognition theory, placing these within a historical context. These principles summarise and integrate across a family of theories with common roots in Vygotsky's conception of mind as culturally constituted. The principles are that activity is mediated by cultural tools, cognition involves looping between brain, body and world, cognition is distributed across people and tools, and learning is the transformation of participation in the ongoing sociocultural practices of a cultural community.

There is a dialectical relation between practice and theory in educational research. On the one hand, in asking particular questions, in using particular methods, and in interpreting results, the researcher's theory of mind becomes manifest. One cannot remain agnostic concerning matters of cognition, and the choices that are made in carrying out a research study imply ontological commitments about the nature of mind and its relation to the world. On the other hand, researchers make ontological commitments concerning matters of mind from familiarity with theory, and thereby shape subsequent investigations around these commitments, from choice of question, to method, to interpretation and reporting. By being intentional, in understanding one's own beliefs about how minds carry out cognition, and in aligning questions, methods, interpretation and reporting with these beliefs, researchers will carry out studies with coherence and depth.

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