An Embodied Future Map for Constructionism

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Constructionism is an approach to learning that focuses on the use of computers as knowledge construction tools. Although it stems from Piaget’s genetic epistemology, constructionism places particular importance on the contextual nature of learning and acknowledges the subjective representations of learners, grounded in their identities and previous social and bodily experiences. Even though constructionism is a strong paradigm in learning sciences, its theoretical assumptions and how these assumptions have changed since its emergence have not been studied. I trace how constructionism has evolved since its emergence, stemming from Piaget’s genetic epistemology, in parallel with the paradigm changes in cognitive science to incorporate embodied and ecological notions of cognition. Embodied theories of social cognition, tool use, and metaphorical thinking are presented for the purpose of discussing implications for constructionist learning design and to reflect on the future of computers as knowledge construction tools.

Initial attempts on using computers in education were grounded in approaches compatible with industrial age values. For example, computer-aided instruction began as a computer-supported implementation of Skinner’s programmed instruction (Skinner, 1954). However as creativity, originality and innovation became more sought after in the information age, educators became more concerned about educating independent, creative and critical thinking individuals. These developments also paralleled societal changes, for example second-wave feminism and environmentalist movements, where the common denominator was the vision of an individual as a free, initiative-taking, adaptive and creative problem solving agent, who has a global scale, big picture world perspective and responsibilities, irrespective of gender and socio-economic background. Use of technology in education acquired a new meaning, from a centralized knowledge disseminator to a personalized knowledge construction tool.

The psychological and epistemological ground for approaching computers as knowledge construction, instead of knowledge transfer, tools were laid by Piaget’s theory of constructivism, as well as previous work on experiential learning, for example by John Dewey. Piaget opened a new window into the inner workings of the human mind, by describing how knowledge structures are built through social and bodily interactions. In his numerous studies Piaget provided evidence for how children built an understanding of basic physical qualities (e.g., conservation of continuous / discrete quantities) and mathematical concepts through experience. He proposed a stage theory of cognitive development, describing the progression from an intuitive to scientific and socially accepted worldview (Piaget, 1954). In addition, Piaget studied the relation between ways
of knowledge construction and the validity of knowledge, bridging psychology and epistemology, two entities that were often thought of separately. Built on a metaphor with genetics, and therefore, called genetic epistemology, this study involves inquiring the origins (genesis) of knowledge to understand its validity. Emphasizing the importance of knowledge construction for meaningful learning, genetic epistemology had strong pedagogical implications.

**Emergence of Constructionism and Its Convergence with Embodied Perspectives**

Seymour Papert, having worked with Piaget, proposed a new approach to the use of computers in education based on Piagetian notions of learning, but with additional emphasis on the building of a public entity, and on the role of the affective and environmental dynamics in learning. Papert’s views were first popularized with his book, titled “Mindstorms: Children, Computers, and Powerful Ideas” (Papert, 1980). Papert first used the term “constructionism” in a NSF grant proposal, and defined it as an approach that is grounded in constructivist theories of psychology with the added notion that learning is most effective when part of the learning activity involves constructing a meaningful product with manipulative materials (Papert, 1986).

The goal of this grant was expressed as creating materials “to make better use of the level of computers” that was becoming common in schools. Papert also emphasized that these materials were to be designed by paying special attention to the role of “affective, cultural and gender-related facets of learning science”, which marks differences with Piaget’s approach to learning.

In addition to the developments in personal computing, the 1970s and 80s witnessed exciting developments in the study of cognition as well. Gibson (1979) challenged the cognitivist account of perception, particularly vision, by proposing that the act of seeing is not merely accepting input through the retina, but an active information processing activity that is coupled with other bodily processes. He criticized perception studies in non-contextualized lab environments, and emphasized the importance of bodily interaction and context in studying vision. He also introduced the term *affordance*, referring to action possibilities of an object for an organism. The affordance of an object for an organism is emergent in the interaction of the agent with the object, and *affordances* are immediately perceived rather than symbolically processed. The strong implication of Gibson’s work was that cognitive mechanisms can only be understood by considering the agent as a situated entity in an environment, and that, sensorimotor (bodily) and cognitive mechanisms are not separated, rejecting the Cartesian duality of mind and body.

Around the same time, Lakoff and Johnson (1980) published an influential book, in which they proposed that conceptual metaphors, allowing the understanding of an abstract domain based on physical and bodily experiences, were not merely a linguistic phenomenon, but were a central theme in how the mind works. Metaphors we use to make sense of abstract domains are grounded in and made possible by our bodily experiences and therefore, cognition is embodied.

In 1980 another seminal work was published by Maturana and Varela, namely “Autopoiesis and Cognition” (1980). Maturana was a biologist. His earlier studies on the vision of frogs and pigeons made him realize that considering vision and in general perception, as the mapping of an, objective, external world, was an inadequate approach.
This approach could not explain a multitude of cases where the sensory experience interacts with certain features of the perceived (e.g., geometrical features interacting with color distinctions), or with the situated activity of the observer, particularly in time-pressured activity. Maturana developed a new approach, in which the activity of the nervous system was considered to be determined only by the nervous system itself. The external stimuli only had the role of triggering an internally determined activity of the nervous system. This approach had a larger implication; perception was not viewed as getting input from an external reality but the activity of constructing one. In their book Maturana and Varela further developed these ideas and proposed a framework to characterize living things as self-referential, self-constructing and autonomous units. They described a cognitive system as a system that defines a domain of interactions for maintaining itself, and the cognitive activity as acting in this domain.

These newly developing notions about the bodily foundations of cognition and the coupling between cognition and the environment resonated with Papert’s emphasis on the role of the bodily/self-related knowledge and the environment in learning. Papert proposed that just like French can be learned in an intuitive and meaningful way when the learner is immersed in a French-speaking environment, such as in France, mathematics could be learned in a mathematically rich, computerized environment. He called this environment Mathland and generalized the notion of an environment that provides rich learning experiences as a microworld. The representations learners construct during their interaction with the microworld has, what Papert calls, “syntonic” properties. Syntonicity refers to the relevance of a concept to knowledge about the self. The underlying idea here is that we learn about new things based on what we already know. Some of what we already know is very much engrained; it is what makes us “us”. For instance, knowledge of our body and of how we bodily interact with the environment is something fundamental, and this knowledge is always available to us. Body syntonicity refers to the notion that we understand a phenomenon by using knowledge about our body. When we learn a new concept based on this type of knowledge, connecting to the sensorimotor schemata, it is “body syntonic”.

Papert developed a computer-programming environment, Logo, as a model for his approach to learning, in particular in Mathematics. Logo is a functional programming language, used to pass commands to a turtle-shaped agent on the screen. The turtle moves according to the commands, leaving a trace behind. While it is possible to pass simple commands, for example to make the turtle go forward, or turn right 30 degrees, Logo also allows creation of a new command, in the form of a function, that involves repetition of a set of commands. Functions can also be put into other functions allowing the creation of increasingly more complex commands. Students’ programming the turtle by using commands and functions resembles one teaching a language to someone. The structures used in this communication get progressively more complex. The discourse in this communication is very ego-centric, in the sense that the student puts herself in the place of the turtle when passing commands describing how to do something, for example to draw a circle. This is unlike other alternative ways of representing a circle. A turtle can be defined as “a collection of an infinite number of dots all with the same distance to a fixed point” or with an algebraic representation, such as “$x^2 + y^2 = r^2$”. While both representations define what a circle is, they do not describe how to draw a circle. The formal description of what a circle does refer to the meaning of a circle for an embodied
agent. If a child is asked to make a circular path by walking in an open area the movement will be to rotate and walk at a constant rate. It is also likely that the most intuitive representation of a circle is the one based on the action of drawing a circle. In Logo this is accomplished by asking the turtle to go forward a fixed distance and turn right or left with a fixed angle. The Logo representation of a circle is intimately related to the first-person meaning of a circle, which is grounded in bodily interaction. The traditional, algebraic, definition of a circle lacks this quality. Use of Logo to represent geometrical objects introduces an alternative body-syntonic representational system (Abelson, 1986).

The idea of body syntonic learning resonates with the embodied view of mind. Papert himself did not discuss how his approach to learning relates to notions of embodiment, possibly because at the time of his theorizing, in the 70s and early 80s, embodied views of cognition were new and budding. However an embodied view of mind had been expressed in the ecological view of perception and these ideas were being discussed in artificial intelligence circles. It is very likely that Papert, being an AI researcher, was aware of the discussions about the implications of embodied and ecological perspectives on AI and could also have thought about implications in education. While comparing his efforts to Piaget’s Papert says, “My perspective is more interventionist. My goals are education, not just understanding.” In its essence constructionism is an approach to education, it is a prescriptive theory of learning, rather than descriptive. Therefore, it is possible that Papert did not think that it would be meaningful to focus on how embodied and ecological views relate to constructionism. This is probably not true anymore. Notions of embodiment had a great impact on human computer interaction (e.g., embodied interaction, tangible computing, ubiquitous computing). Given the focus on use of computational tools as objects to think with in constructionist applications, now we are in a time where an embodied view of mind and constructionist approaches to learning are naturally converging.

Learning, Human Computer Interaction and Embodiment

The notion of building entities with computers was transformed with changes in personal computing and human computer interaction. In the early 80s introduction of graphical user interfaces (GUIs) and the mouse ignited a new era in HCI leading to a paradigm of desktop computing based on a metaphor between the office space and the computational environment. These were steps towards designing a more intuitive interface. The office space metaphor was effective because it drew knowledge about physical interactions in the office space to represent computational processes. For example, dragging and dropping a file into a folder was a metaphor for copying piece of data from one point to another. In Papert’s term interactions in this interface were body syntonic. Since then, designing more intuitive interfaces has been the goal in human-computer interaction, to take advantage of natural human interaction capabilities. This effort is largely based on cognitive science research (e.g., Norman's 1999 implementation of Gibson’s affordance idea for interface design).

The changes in human computer interaction also affected the constructionist movement. The personal computer provided a flexible environment for construction of computational objects, nevertheless its physical form did not allow for modification. Although Logo was first designed to control a mechanical “floor turtle” in the late 60s, the turtle moved to the digital realm shortly after, never to come back until the early 90s,
when researchers at MIT returned to studying the interaction between the computational and the physical world.

Computers’ lack of interaction with the physical world yielded to a collaboration between MIT researchers and Lego toy bricks company. At the time Lego construction kits did not include any programmable elements and lacked sensors, making it impossible to create robots showing complex behaviors. On the opposite end the Logo turtle was programmable but lacking physical components. The vision that combined Lego and Logo was expressed as, “...instead of controlling and manipulating worlds in the computer, what if children could control and manipulate computers in the world” (Resnick, Martin, Sargent, & Silverman, 1996, p. 1). This effort eventually yielded to the creation of Lego Mindstorms, which includes a programmable brick, activators (e.g. motor) and sensors interaction (see McNerney, 2004 for a review of the evolution of Logo and tangible computing).

Traditionally the personal computer is centralized and affords limited modes of interaction (mainly through keyboard & mouse). A new paradigm, namely ubiquitous computing, emerged in the mid 1990’s that focused on distributing computation in the environment, to better take advantage of natural human abilities and tendencies (Millard & Soylu, 2009). Lego Mindstorms follows this trend. Two main trends emerged in ubiquitous computing. The first one, called “calm computing”, proposes “a new way of thinking about computers, one that takes into account the human world and allows the computers themselves to vanish into the background” (Weiser 2009). According to this view computing is distributed but also hidden in the environment. A second vision is based on Roger’s (2006) conceptualization that focuses on designing UbiComp technologies for engaging user experiences. It argues “for a significant shift from proactive computing to proactive people; where UbiComp technologies are designed not to do things for people but to engage them more actively in what they currently do. Rather than calm living it promotes engaged living...” (p. 406). Furthermore, it asserts that people, rather than computers, should take the initiative to be constructive, creative and, ultimately, in control of their interactions with the world. Dourish shares Roger’s vision and extends embodiment to HCI noting “we encounter, interpret, and sustain meaning through our embodied interactions with the world and with each other” (2004, p. 127). Therefore, it makes sense to design interfaces and interactions taking advantage of the natural ways with which humans communicate.

Lego Mindstorms, and other efforts combining logo and tangible computing, is aligned with Roger’s approach, with its goal being “giving much greater control to users so that they can create their own ubiquitous- computing activities” (Kafai & Resnick, 1996, p. 162). My view is that constructionism has always been compatible with a ubiquitous and embodied approach to computing. Nevertheless, the coevolution of technology and HCI vision that made ubiquitous and embodied interaction possible emerged two decades after the invention of the Logo language. In a 1991 paper, Turkle and Papert emphasized the importance of the concreteness provided by the computer.

The computer stands betwixt and between the world of formal systems and physical things; it has the ability to make the abstract concrete. In the simplest case, an object moving on a computer screen might be defined by the most formal of rules and so be like a construct in pure mathematics; but at the same time it is visible, almost tangible, and allows a sense of direct manipulation that only the
encultured mathematician can feel in traditional formal systems (Turkle & Papert, 1991, p. 163).

My intention in this background section was to provide a historical context for the emergence of constructionism as an educational approach and of embodied cognition as a paradigm of cognition, and how the two historically converged. In the next section I dwell on how different expressions of embodiment can be incorporated with sociocultural and situated approaches to provide a more sound theoretical foundation for constructionist learning design. This is important not only because embodied cognition is becoming the dominant paradigm in cognitive science and related fields, but also because constructionism, since its early inception, has been compatible with some of the main tenets of embodied cognition, and there is need for reflection about what embodiment means for constructionism.

The term “different expressions of embodiment” refers to a set of ideas and research programs that are distinguished not only by what they explain (e.g., social cognition, language, tool use) but also by the fields that they originate from. The beginning of the embodied cognition research program is often marked as the early 1980s. The two seminal works, often cited to mark the start of the embodied cognition research program, “Metaphors We Live By” (Lakoff & Johnson, 1980) and “Autopoiesis and Cognition” (Maturana & Varela, 1980) differ both in terms of their focus as well as the disciplines they are grounded in. Lakoff and Johnson’s work on conceptual metaphors is grounded in a cognitive-linguistic tradition, while Maturana & Varela’s work is essentially a biological theory of cognition. The beginning of embodied cognition as a cross-disciplinary research program that encompasses not only multiple fields but also varied research methodologies yielded to distinct development of embodied theories across multiple disciplines. Today research about how cognition is grounded in bodily processes is conducted in various fields, including evolutionary biology, cognitive neuroscience, traditional fields of psychology, robotics and artificial intelligence, and education to say the least. This yields to an incredible richness in research methods as well (e.g., behavioral experiments, neuroimaging & neuropsychological studies, cognitive modeling, linguistic analysis, phenomenological studies). This is unique compared to previous paradigms of cognition. For example behaviorism was characterized by conditioning experiments, and interventions developed based on these experiments in practice fields. Furthermore people who did the original research and devised interventions based on the original research considerably overlapped, particularly early on, for behaviorism (e.g., Skinner’s work on programmed instruction and Watson’s work on advertising). Another marked difference, compared to behaviorism and cognitivism is, how rapidly research on embodied cognition was interpreted by and influenced social sciences and arts. Part of the reason why embodiment was appealing to social scientists was because the idea of the embodied mind, in particular its implications for theory of mind and consciousness, were to some extent compatible with phenomenological approaches (Dreyfus, 1996).

While what I call “different expressions of embodied cognition” originate in different traditions they share some fundamental assumptions about bodily foundations of human cognition (Wilson, 2002; Ziemke, 2003). In addition, there is considerable new interdisciplinary work merging embodied theories from different orientations to provide a more unified theory of the embodied mind that encompasses different levels of
expression, such as linguistic, behavioral, neural, phenomenological (for examples see Gallese & Lakoff, 2005; Lutz & Thompson, 2003). Therefore the different expressions of embodiment discussed below are not mutually exclusive in what they aim to explain.

**Expressions of Embodied Cognition and Implications for Learning**

**Social Cognition**

Socio-cultural and situated theories of learning put particular focus on social interaction during the learning process. However these perspectives approach social interaction as a cognitive/mental phenomenon with no special bodily involvement.

Since the 1980s neuroscience studies have shown that primates have a specialized system for understanding the actions of other individuals - through mental simulation of the interacted party’s behaviors (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996). Action understanding is a crucial skill for coordination and collaborative goal-oriented behavior of a group of individuals. But going beyond action understanding, this system also allows the simulation of the mental state of another individual during social interaction.

The theory of mind question, how we understand the mental states of other individuals, “mind reading”, has long been discussed in cognitive science and social psychology. There are two main theories explaining this phenomenon. According to theory theory (TT), mind reading is possible by theorizing about the inner states (e.g., desires, beliefs) of another individual and predicting the observable behaviors based on the assumptions about these inner states. This is akin to developing a scientific theory about an observable phenomenon based on some unobservable, theoretical, constructs.

TT approaches social interaction as a disembodied, cognitive phenomenon. A second approach, simulation theory (ST), asserts that humans understand other people’s mental states by adopting their perspective. According ST mind reading involves simulation of the perceived conditions of another individual, and matching the inner state of the observed individual with the resonant states of the self.

Discovery of a cortical mechanism in the monkey brain that activates motor areas during observation of goal-directed actions, to match observation and execution of goal-directed motor actions and accumulating evidence for a similar mechanism in the human brain (Grezes, Armony, Rowe, & Passingham, 2003; Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010), now called the Mirror Neuron System (MNS) have led to the idea that skills like action understanding, imitation and mind reading are made possible by a sensorimotor simulation system. This system allows us to simulate the motor behavior and internal states of an observed individual to make sense of social situations (Gallese & Goldman, 1998).

MNS and its implications in social cognition inspired researchers to provide embodied accounts for human communicative behavior, incorporating an evolutionary perspective (see Arbib, 2002; Fogassi & Ferrari, 2007; Gentilucci & Corballis, 2006; Rizzolatti & Arbib, 1998). These accounts trace humans’ unmatched verbal skills to simple skills such as grasping, action understanding and imitation, providing an evolutionary continuity for language development from early primates to humans. These theories share the core idea that a MNS for motor behavior, especially for hand movements, is the antecedent of verbal communicative behavior in humans. The proposed evolutionary trajectory involves, first the development of a mirror system that matches observation and execution of hand movements for action understanding, then...
emergence of the ability for imitation, followed by a manual (or gesture) based communication system, and the development of the vocal system, ultimately leading to complex human languages.

The evolutionary move from the ability to imitate to gesture based communication has made it possible for humans to express intentions by engaging in symbolic actions. For example, pretending to throw a spear to invite someone to go hunting requires a first level of abstraction where the action represents a communicative meaning instead of being a goal-directed hunting behavior.

This type of communication (and what might follow it, e.g., going to hunting) requires multiple levels of, recursive, theory of mind activity. First the communicator has to execute the action expressed while simulating the mental state of the other party (e.g., my friend is in listening mode, to understand what I am trying to communicate). The listener has to simulate the action observed to interpret its meaning, which constitutes a first level of mental simulation, based on the assumption that the performing party intends to be communicative, which is the second level of mental simulation. Understanding the meaning of the action observed, and if it is executed for a communicative purpose requires evaluation of both the environmental cues (e.g., time of the day, location), and historical and cultural background (past history with the observed individual, culture and habits of the tribe etc.). Furthermore, because communication is a time-pressured activity, comprehension has to happen in a situational continuity, which makes it possible to predict, for example, whether the observed action is communicative, merely based on what took place previously.

The development of the vocal system occurred to allow for associating actions (like throwing a spear) or qualities (physical and emotional or mental states) with certain sounds. Sounds made it possible to create negotiated shortcuts for overt behaviors with symbolic meanings. Once this association is gradually established within a certain group, the sound was used as an anchor point for a negotiated action. Use of the vocal system for communicative purposes allowed both a multimodal way of communication (gestures, facial expressions and vocalizations), and also the development of a complex grammar.

Socio-cultural and situated theories of cognition submit to the idea that meaning emerges from the context within a situated continuity. History and culture shape the semantics of the lived experience. However, these theories do not explain, first how situatedness map to how the brain works, and secondly the role of the body. For example social constructivist theories focus on the negotiated construction of meaning within a socio-cultural context, without explicating how these mental structures are processed in the brain, and how the bodily states shape the lived experience of now. Embodied simulations provide explanations for these across neural, behavioral (third-person account), and the phenomenological (first-person explanation) levels. At the neural level there is accumulating research about the neural pathways participating in embodied simulations (for example Svensson, Morse, & Ziemke, 2009), furthermore, there are theories of how embodied simulations can constitute the source for semantic content for social cognition (Gallese & Sinigaglia, 2011).

Apart from proposing a theoretical shift towards approaching social cognition as embodied simulation, social embodiment has two obvious implications for learning. First, mimicry and imitation are not simple acts of copying behavior but rather an attempt to reconstruct the lived experience of another individual for the purposes of learning and
making sense of the observed behavior. Imitation is not about perceiving actions and replicating them by motor behavior, it is rather adoption of the agency of another individual within a context, to produce similar introspective states, accompanied by matching overt motor. The leap from action understanding to imitation is proposed to be one of the major steps in the evolution of language and thought. Imitation is also not unique to humans and observed in some other animals, most noticeably in chimpanzees reared by humans, at a level comparable to young humans (Whiten & Custance, 1996). The ability to simulate the mental state of another individual and re-enact the observed behaviors is arguably the most fundamental learning mechanism for humans. It is our shortest path to adopt norms and practices in a new social context, and has served for transmission of culture since early human evolution.

Although the importance of imitation in social learning was recognized early on, the processes underlying imitation were laid in a disembodied, cognitivist framework. For example Bandura (1969) proposed that imitation involved coding of the modeled stimuli into images and words for memory representation, later to be retrieved for the reproduction of the observed behavior. The traditional approaches consider imitation as a copying of behavior, motivated by reward conditions. From an embodied perspective imitative behavior is an attempt to make sense of the actions of another individual through simulation of introspective and sensorimotor states, and re-enact them. Learning is not defined as storage of a collection of disembodied images and words in memory, but a change in the neural system to allow for partial simulation of sensorimotor and introspective states active at a given instance, at a later time.

The second implication involves rethinking the role of gestures in learning, thinking and social interaction. Gestures accompany speech across cultures, and facilitate communication. Aforementioned theories of language evolution (for example Arbib, 2005) point to a neural system originally used first for action understanding, particularly of hand movements, for both the antecedent manual-based communication system and complex human languages. Brain imaging and clinical studies provide further support for the idea that gesture and verbal language production and comprehension make use of a shared fronto-parietal network active in embodied simulations, the mirror neuron system. Gestures are therefore an integral part of human communicative behavior. Additionally gestures play a non-communicative role in thinking and learning. The role of gestures in learning is perhaps the most studied topic in regard to the bodily foundations of learning. There is now ample research about the multiple roles gestures play in human cognition and communication. For example, gesture-speech mismatches were found to indicate readiness for learning (Garber & Goldin-Meadow, 2002), and using gestures reduces cognitive load (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001) and increases retention (Cook, Mitchell, & Goldin-Meadow, 2008). These have strong implications for learning design. For example, children’s use of finger counting during arithmetic should be viewed as a cognitive off-load mechanism, or more technically a feedback loop for embodied simulations through recursive activation of motor and visual circuits, and not an indicator of cognitive deficiency (finger counting is still not allowed in many schools around the world). Additionally teachers’ ability to make sense of, especially young, students’ gestures can make a difference in understanding the students’ readiness for learning a particular skill. This has implications also for the design of the physical setup of a classroom or the online learning space. Given the importance of gestures, the
learning environment should allow students’ to have visual access to each other’s gestures, postures and facial expressions.

From an embodied perspective, behavior can no longer be understood by limiting its scope to syntactic production and comprehension of vocalized words. Bodily states, such as postures, arm movements, gestures, and facial expressions, enacted during social interaction should be considered to be an integral part of communicative behavior in addition to language (McNeill, 1992). This is not only about expanding the scope of analysis in understanding learning in a social context but shifting the perspective about what social cognition is, how it evolved, and the underlying processes involved. The embodied simulations approach is pervasive and constitutes the grounding for explanations in other domains of cognition as well, proposing a single mental system for all cognitive phenomena. Tool use is one of them.

**Tool use**

In its limited definition tool use can be described as use of an external physical entity to enhance human manipulative capabilities. In its broader definition a tool can be described as a construct that allows manipulation of other objects, including digital and conceptual entities. First I will cover tool use in its limited definition and will go back to the broader definition later.

While other animals show a limited ability to use tools (e.g., use of a stick to retrieve food), humans have an unmatched ability to construct tools and use them showing a deep understanding of their body and how it is situated in a physical environment. Two foundational and distinct systems are proposed to be functional in the use of tools.

The first one allows for the semantic access to the affordances of a tool based on, essentially visual but also tactile and auditory, stimuli. While the mirror neuron system represents neural circuitry that is active both during observation and execution of actions by a conspecific, another set of neurons respond to stimuli from objects. This group of neurons, namely canonical neurons, distributed in a set of parietal and premotor areas (particularly F5), were found to discharge in monkeys both during the execution of grasping movements and as well as when the subject sees the object in stationary form (Rizzolatti & Fadiga, 1998). In an fMRI study with human subjects a homologue canonical system has been found (Chao & Martin, 2000). A network of left premotor and parietal regions were found to be active when subjects were shown pictures of tools, and were asked to either silently name them or just observe. Other conditions included presentation of animals, faces and houses, which did not trigger similar level of activation in this system, leading to the idea that canonical neurons are specialized to respond to manipulable objects. Chao and Martin proposed that our ability to identify tools might depend on the re-activation of sensori and motor experiences attributed to the object viewed. An important finding here is that the areas activated during the identification of the tools considerably overlap with premotor areas activated during another experiment where subjects were asked to imagine right hand movements (Grafton, Arbib, Fadiga, & Rizzolatti, 1996). This suggests that identification of a tool involves re-activating sensorimotor circuits characterizing the activity that would take place during the interaction with the tool. The implication here is that the semantics of objects around us emerge from our history of interactions with them. We simulate possibilities of
interactions with objects when we merely see them. Our previous interactions shape our immediate perception. In this sense, identification of an object is not about retrieving physical attributes of an object category stored in the memory and comparing it to the perceived stimulus, but rather about the visual features of the object triggering a motor program that was created either during previous direct interaction with the object or observation of another individual interacting with it.

The second system is involved in the use of a tool. There are a series of clinical studies showing that the two systems for the identification and use of the tool are dissociable (patients can have disruptions with one system without affecting the other one). The terms ideational and conceptual apraxia are used to identify these conditions, the latter one referring to disruptions with identification of a tool and the former one for a disorder of learned motor skills involving tools (see Johnson-Frey, 2004 for a review). What is the evolutionary advantage of this dissociation? Being able to acquire a conceptual understanding of a tool even when a direct motor interaction with the tool is not a previous experience is possibly an advantage. Furthermore, this also suggests a dissociation of the semantic system, grounded in the sensorimotor system, from a motor skill system. This dissociation might be the necessary ground to allow execution of motor tasks while at the same time continuing conceptual processing, which might have developed as a result of the coevolution of culture and the human brain in the recent history of human evolution.

Social learning, most importantly imitation learning, played an important role for the dissemination of tool use across human cultures. The ability to learn how to use tools, to recognize them and to retrieve motor programs making it possible to use the tool constituted a strong selective pressure for early hominid groups, most probably starting with Homo habilis. This yielded to changes in brain size, accompanied with changes to the digestion system to accommodate a bigger brain (Leonard & Robertson, 2005). Human hands and sensorimotor brain circuits related to hands also changed to accommodate fine motor skills required for better tool use. The story about the coevolution of different systems in hominids can go on, but the point to be taken is that human body and brain has evolved to allow tool use, to learn about how to use tools from others and to disseminate this knowledge. Humans are inherently tied to tools. We can’t run fast, jump high, and we have a weak immune system compared to other mammals. But we can make and use tools. We make sense of using tools in a social context and the embodied simulation system used during social cognition and during tool use overlap.

The embodied perspective provides a unified explanation of processes that underlie social interaction and tool use. First, learning how to use a tool from another person engaging in goal-directed behaviors using the tool is done by a theory of mind activity, which involves the simulation of the sensorimotor and introspective, particularly, intentional states. This implication is captured best in apprenticeship models, where emphasis is given to the interaction of the learner with an expert at work. This also happens when learners build things in a social context, such as the case in constructionist learning. Secondly, the ability to recognize the affordances of a tool is dissociable from the ability to use the tool. One having a complete understanding of what the tool does, does not imply the ability to use the tool (and in some conditions, such as conceptual apraxia, the opposite is also true). Being able to learn how to use a tool requires direct experience with using the tool. While a demonstration can yield to the learner’s partial
sensorimotor and introspective simulations of tool use, this experience does not inform the user about how the tool couples with his/her own self, with her own idiosyncrasies. A third implication is that the knowledge about a tool is inherently embodied, and is based on previous, either observational or direct experience with the tool. Previous experiences with a tool directly structures how the tool is perceived, and in general our physical and social experiences in an environment shape our immediate perception. In this sense students’ previous experiences shape how they perceive the affordances of objects around them, in addition to the intentional states they assign to goal-directed behaviors of other individuals they encounter. Extended interaction with a tool also changes how a human perceives and interacts with the environment using the tool. The changes here happen at the perceptuo-motor level; in a sense the tool becomes part of the cognitive system (Clark & Chalmers, 1998).

In his book *Mindstorms*, Papert reflects on how he was fascinated with gears as a child and how his experiences with the gears later made it easy for him to make sense of an equation with two unknown variables, since it was just a mathematical expression of how the gears work. Later, when he read Piaget’s work it immediately became clear that what happened to him with gears and equations was assimilation, the understanding of a new construct based on an existing schema. However, two things were missing from Piaget’s theory of assimilation.

First, Piaget does not emphasize the affective aspects of assimilation. In Papert’s own words “there was feeling, love, as well as understanding in my relationship with gears.” Piaget’s theory is strictly cognitive and cannot not accommodate how the notion of gears can trigger such emotional states. The embodied simulations theory does, because it refers to the partial simulation of both sensorimotor and introspective states as the source of meaning. This applies to identification and use of tools as well. Many of us show an emotional reaction at the sight of a weapon, because identification involves simulation of introspective states acquired previously in regard to the object. The point I am trying to make here is that embodiment does not only explain how cognition is grounded in bodily systems, i.t is also an attempt to bring affect to the domain of cognition.  In this sense, the emphasis on the role of affect in learning is better accommodated from an embodied perspective.

Secondly, in addition to serving as a connection to formal mathematics, gears connected with Papert’s bodily knowledge. “You can be the gear, you can understand how it turns by projecting yourself into its place and turning with it.” His previous experiences with gears allowed him to simulate how gears worked, and later this constituted the grounding for his understanding of equations. This taps into one of the major foci of study in the embodied cognition program; how knowledge in a physical domain can help to structure knowledge in an abstract domain by use of metaphors.

**Metaphorical Thinking**

The study of metaphors in human thinking began with study of metaphors used in language samples in cognitive linguistics. Lakoff and Johnson (1980) proposed that humans’ conceptual worlds, governing their day-to-day experiences, are largely metaphorical. Here a metaphor is defined as a mapping from a familiar source domain to make sense of a novel target domain. Since many of our intuitions, knowledge and assumptions are deeply rooted in our body our bodily experiences often constitute the
source domain. However, bodily experiences take place in a socio-cultural context, and therefore bodily experiences are not merely physical but are coded based on cultural presuppositions.

Since language is a primary expression of our conceptual world Lakoff and Johnson focused on the study of metaphors in language. This is not to say that conceptual metaphors are used only in language; their claim was that all cognition was metaphorical and language was a good place to start. Work on metaphors progressed, later to include such notions as image schemas, conceptual primitives about spatial relations (Johnson, 1987), aspect schemas, structures coding events with temporal dimension, and conceptual blends, structuring of a new domain by way of blending multiple domains (Tunner & Fauconnier, 1995).

While the study of conceptual metaphors in language samples provided some evidence for bodily groundings of cognition, the early body of work on conceptual metaphors were ironically cognitive (based on proposed cognitive structures); these theories did not explain how metaphors are processed at the neural level and there was no psycholinguistic evidence to support the claims. As previously mentioned, the embodied cognition research program emerged in multiple disciplines in the early 1980s and it took more than a decade for unified, cross-discipline, explanations to emerge. One such theory for metaphorical thinking proposes that metaphorical thinking occurs by mental simulation of the actions described in the metaphor (Gibbs, 2006). Evidence for two propositions are needed to support this claim; first, sensorimotor systems are used to understand non-metaphorical language and, secondly, metaphorical use of language activates sensorimotor resources that would be active in the understanding of the non-metaphorical meaning (e.g., grasp the concept).

There are a multitude of studies showing that understanding the actions described in a sentence recruits relevant sensorimotor resources (see Gibbs, 2006 for a review). For example, Buccino et al. (2005) showed that action-related sentences, particularly involving hands and feet, modulate relevant parts of the motor system. A simulation theory is proposed as one possible explanation for this phenomenon: “. . . the understanding of action-related sentences implies an internal simulation of the actions expressed in the sentences, mediated by the activation of the same motor representation that is involved in their execution” (Buccino et al., 2005, p. 361).

Two qualitative studies provided evidence for the second proposition. The first study showed that watching, imitating, or imagining the action in an abstract metaphor improved subjects’ ability to imagine what is described in the abstract metaphor (Gibbs, Gould, & Andric, 2006). For example, watching, imitating or imagining the grasping movement before listening to the grasp the concept metaphor facilitated imagining the metaphorical meaning. They explain this phenomenon by arguing that: (a) “People’s understanding of metaphorical language involves their engaging in embodied simulations that in the case of expressions like “stretch for understanding” and “chew on the idea” make these phrases both understandable and conceptually plausible” (p. 222), and (b) “Having people watch, imitate, or imagine engaging in relevant embodied actions (e.g., chewing or grasping) may enhance the degree to which they conceptualize metaphorical actions through embodied simulations” (p. 224). In the second study (2007), it was shown that in two reading time tasks performing or imagining body movements appropriate to metaphorical content before reading metaphorical phrases improved participants’
immediate comprehension of these phrases.

An fMRI study, where no neural congruence between observations of hand, foot and mouth movements and understanding metaphors with relevant actions (e.g., grasp meaning) provides conflicting evidence in regard to use of bodily simulations in understanding metaphors (Aziz-Zadeh, Wilson, Rizzolatti, & Iacoboni, 2006). A difference in processing between novel and familiar metaphors is proposed as an explanation. In a novel metaphor the salient feature is the non-metaphorical meaning of the action word, and once the metaphor becomes familiar the metaphorical meaning (e.g., understanding the meaning vs. grasping) is salient, reducing reliance on the original action processing (Aziz-Zadeh & Damasio, 2008).

How the metaphors are processed in the brain and the study of the role of embodied simulations in understanding and production of metaphors is still new, with many open questions. Nevertheless the idea that metaphors, linking our physical experiences with novel conceptual domains, are central in our thinking has implications for learning design. Constructionism puts particular emphasis on how bodily knowledge can structure learning in complex domains. Papert’s reflection on how his knowledge of gears helped him learn equations (Papert, 1980) can be characterized as mapping the inferential structure of the physical source domain, gears, to a target domain, the two variable equations. He was able to engage this type of metaphorical thinking due to his previous bodily experience. Therefore one implication here is the idea that the learning activities should give the learners’ opportunities to come up with metaphors to relate what they are learning to their previous experiences that is both bodily and personally relevant to them. A second implication is about the subjectivity in the way one makes sense of a new domain. Having different bodies and different socio-cultural experiences, we rely on different domains in constructing metaphors. The learning environment should allow for such pluralism. I believe that this is realized in constructionist learning. Construction activity is in a sense a self-exploration of how existing notions and previous experiences can be related to a new learned domain. A third implication is for research. Although metaphors in thinking was first studied from language samples, how metaphorical thinking supports learning should be studied by focusing on the activities of learners within a context overtime. Gestures, conversations with classmates, entities built, and interviews can all provide clues about the metaphorical thinking of learners, since metaphorical thinking itself is action and not symbol manipulation.

The Agent Perspective and Embodied Simulations

In Logo the user can create geometric shapes by projecting the self on the turtle, or thinking like the turtle. This activity is body syntonic because one can use knowledge of movement in real physical space to draw shapes with the turtle. It is ego syntonic because it acknowledges the existence of the user with affective states, and provides opportunities to reflect this on the turtle’s movement (e.g., creating an aesthetic geometric pattern). Wilensky and Reisman (2006) proposed an embodied modeling approach using NetLogo, an agent-based modeling tool (Wilensky, 1999), to provide learners opportunities to build a model of biological phenomena, such as predator and prey population relations and the synchronized flashing of fireflies. The embodied modeling approach described is essentially an agent-based approach to modeling, in which rules of interaction among different elements are described at the individual level.
as opposed to the aggregate (differential-equation) based approach. However what makes this approach embodied is that it gives learners the opportunity to put themselves in the place of an agent and develop rules describing the behaviors of the agent, only then to run the model and observe the complex patterns emerge from the interaction of many simple elements. The general goal is described as to help students construct a decentralized and probabilistic understanding of complex phenomena, encompassing multiple levels. The authors propose that mistaken assumptions about the nature of the phenomena would be easier to diagnose for this approach in comparison to the study of an aggregate level formula for two reasons. First, the embodied modeling approach offers feedback to the learners at two levels, the individual and the aggregate level, which means more ways of finding errors with the model for further improvement. The second reason is that students are better in understanding the rules at the individual level (as opposed to an aggregate formula) because “students will often try to make sense of a given rule set by assuming the perspective of the individuals within the model and using their imaginations” (p. 186). Beyond helping with spotting errors with the model simulating the agency of an individual in the model is proposed as a powerful aspect of the embodied modeling approach: “When their knowledge of the individual biological elements is combined with their knowledge of their own embodiment, their own point of view, they are enabled to think like a wolf, a sheep, or a firefly” (p. 203).

Why is it better to assume the role of an agent situated in a system (agent-based thinking) in our attempts to understand a complex phenomenon? What makes it tap into the way our minds work? First agent-based thinking requires a theory of mind activity about how it would be to be, for example, a firefly. As it was discussed earlier, embodied simulation of the sensorimotor and introspective (e.g., intentional and emotional) states, either of another individual or the self, is a central mechanism in human cognition. In this sense adopting an agent-based perspective resonates with the usual way we make sense of our world.

But how can humans have the ability to develop a theory of mind of a non-conspecific? Our social interactions were never limited to only humans. There was always strong selective pressure to mind-read both hostile (e.g., bears) and friendly animals (e.g., dogs during co-hunting). In addition humans have historically assigned human attributes to both other living and non-living things (anthropomorphism), to make sense of their surroundings (e.g., “the river god is angry”, after a flood).

The agent-based perspective involves developing a sense of the affordances of other objects in the microworld, from the eyes of an individual agent. This is another skill that humans are extremely good at. Simulating the mental-state of another individual allows us also to make predictions about how that individual might interact with the objects in the environment. This has endless use, like coordination of behavior and prediction of peril. Therefore the projection of agency on a sheep in the model also involves seeing the microworld form the eyes of the sheep.
Conclusion

This paper is an attempt to initiate a discussion about the theoretical foundations of constructionism and what we have to learn from new findings in embodied cognitive science, in order to design learning environments that take advantage of the natural ways with which humans think and interact. To this end, I provided a review for the emergence of constructionism as an approach to use of computers in education and traced its evolution in parallel to changes in cognitive science and human computer interaction. I focused on three expressions of embodiment, social cognition, tool use and metaphorical thinking, and discussed how constructionist notions of learning and design can be interpreted from the lens of these expressions.
References


