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Mental Modeling in Conceptual Change

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Introduction

The nature and processes of "conceptual change" are problems that are of considerable interest to researchers across several disciplines occupied with developing understandings of science, learners, or cognitive development. Although the problems and methods to address them have different formulations in these areas, there is a long history in each of specifying the beginning and ending states of deep conceptual changes, such as what constitutes the nature of representational changes from Newtonian mechanics to the theory of relativity, or from a "naive" understanding of physical phenomena to a scientific understanding provided by physics or biology, or from individual early (possibly innate) representational structures to adult community representations of a whole range of phenomena, including of other humans, during processes of cognitive development.

A major outstanding problem in all of these areas is the nature of the processes - or “mechanisms” - through which concepts and conceptual structures change. In part because of similarities in features of conceptual changes across these areas, such as ontological shifts and degrees of “incommensurability,” some, myself included, have proposed that the same or related processes are at work in the several kinds of conceptual change. Clearly one would expect differences between, for example, the practices used by scientists in constructing new concepts and students learning new (for them) concepts. For one thing scientists have articulated theoretical goals and sophisticated metacognitive strategies while children and students do not. However, in conceptual change processes, a significant parallel is that each involves problem solving. One way to think of learning science, for instance, is that students are engaged in (or need to be enticed into) trying to understand the extant scientific conceptualization of a domain. In this process, learning happens when they perceive the inadequacies of their intuitive understandings - at least under certain conditions - and construct representations of the scientific concepts for themselves. The impetus for a problem solving process can arise from many sources: acquiring new information, encountering a puzzling phenomenon, or perceiving an inadequacy in current ways of understanding.

Concepts provide a means through which humans make sense of the world. In categorizing experiences we sort phenomena, noting relationships, differences, and interconnections among them. A conceptual structure is a way of systematizing, of putting concepts in relation to one another in at least a semi - or locally - coherent manner. But a conceptual structure is complex and intricate and it is not possible to entertain it in its entirety all at once. Trying to understand new experiences or how a concept relates to others can reveal heretofore unnoticed limitations and problems in the representational capabilities of current conceptual structures and even reveal inconsistencies with other parts. Although how reflectively they engage in the process differs, scientists, learners, and developing children all engage in this kind of sense-making which suggests that to a greater or lesser extent conceptual change is a reasoned "change in view" (Harman, 1986).

Thinking of conceptual change in this way focuses attention on the nature of the reasoning scientists use in solving representational problems. Creating models as systems of inquiry is central in the problem solving practices of scientists. There is a large literature in history and philosophy of science that establishes that processes of constructing and manipulating analogical, visual, and simulative models play central role in episodes of conceptual change across the sciences. On the account of conceptual change in science I have been developing, reasoning through such models ("model-based reasoning") provides a significant means (not necessarily the *only* means) through which conceptual innovation and change occur (see, e.g., Nersessian, 1992a, 1992b, 1995, 1999, 2002b). Within both philosophy and cognitive science the traditional view of reasoning is identified with logical operations performed on language-like representations. In contrast to these traditional conceptions, these modeling practices of scientists are not simply aids to logical reasoning but constitute a distinct form of reasoning. Loosely construed, a model is a representation of a system with interactive parts with representations of those interactions. Models are representations of objects, processes, or events that capture structural, behavioral, or functional relations significant to understanding these interactions. What is required for something to be an instance of model-based reasoning is that: 1) it involves the construction or retrieval of a model; 2) inferences are derived through manipulation of the model; and 3) inferences can be specific or generic, that is, they can either apply to the particular model or to the model understood as a model-type, representing a class of models.

To understand how model-based reasoning leads to conceptual change requires both detailed investigations of cases of their use in conceptual change and of their basis in human cognition - what I have called a "cognitive-historical" analysis. The latter requirement stems from a "naturalist" epistemology which holds that the problem-solving practices of scientists arise out of and are constrained by basic cognitive capacities exhibited also in mundane problem solving, though of course not from these alone. The normally functioning human cognitive apparatus is capable of mental modeling, analogy making, abstraction, visualization, and simulative imagining. The sciences, through individual and collective efforts, have bootstrapped their way from these basic capabilities to the current state of play through consciously reflective development of methods of investigation aimed at gaining specific kinds of understanding and insight into nature, such as quantitative understanding. Of course, the development of these methods has been and continues to be a complex interaction among humans and the natural and socio-cultural worlds in which they are embedded. Nevertheless, an important part of explaining how these investigative strategies fulfill their objectives requires examining the nature of mundane cognitive capabilities out of which they arise.

In this paper I will focus on one capacity, that for mental modeling, in part because analogy, visualization, and simulation contribute to reasoning through mental modeling and in part because mental modeling is a central notion used in analyses of conceptual change across the literatures of studies of science, learning, and cognitive development. For an intuitive understanding of what it means to solve a problem through mental modeling, consider the situation where a large sofa needs to be moved through a doorway. The default approach to solving the problem is usually to imagine moving a mental token approximating the shape of the sofa through various rotations constrained by the boundaries of a doorway-like shape. In solving this problem people do not customarily resort to formulating a series of propositions and applying logic or to doing trigonometric calculations. Note, too, that arriving at a problem solution is easier if it takes place in front of the doorway and the sofa, as opposed to in a furniture store and thinking about whether it is wise to purchase the sofa. In such mundane cases the reasoning performed via mental modeling is usually successful, i.e., one figures out how to get the chair through the door, because the models and manipulative processes embody largely correct assumptions about every-day real-world phenomena. In scientific problem solving, where the situations are more removed from human sensory experience and the assumptions more imbued with theory, there is less assurance that a mental modeling process will be successful. More sophisticated and explicit knowledge of constraints relating to general principles of the science and mathematical equations will play a role in constructing and manipulating the mental models. There are four points to highlight from the mundane case that carry across in considering the case of science: 1) humans appear able to create representations from memory that enable them to imagine being in situations purely through mental simulation; 2) the imagining processes can take advantage of affordances in the environment can make problem solving easier; 3) the predictions, and other kinds of solutions arrived at through this kind of mental simulation are often correct -or good enough - in mundane cases; and 4) when solution fails a wide range of culturally available tools can be used, such as getting out the measuring tape and making the calculation.

Having wrestled with a considerable portion of the cognitive science literature on mental models, I have to concur with Lance Rips' observation that much use of the notion appears "muddled" (Rips, 1986), but I disagree with his conclusion that dismisses the viability of the notion entirely. A potentially quite powerful notion can be articulated and, as some researchers have contended, could provide a much-needed unifying framework for the study of cognition (see, e.g., Gilhooly, 1986; Johnson-Laird, 1980). My objective here is modest: to provide a much-needed clarification of reasoning through mental modeling; one that is consistent with the cognitive science research on mundane cases and is adequate as a cognitive basis for the scientific model-based reasoning practices exhibited in conceptual change, which can then be investigated further in empirical and theoretical research in cognitive science.

Thinking about the scientific uses has required extending my investigation beyond the literatures specifically on mental models to include research on imaginative simulation in mental imagery, mental animation, and perception-based representation. Further, within traditional cognitive science, the representations and processing involved in reasoning are held to take place "in the head," and reasoning is analyzed as detached from the material environments in which it occurs. Although it is possible that simple model-based reasoning might take place only "in the head," reasoning of the complexity of that in science makes extensive use of external representations. A wide range of data - historical, protocol, and ethnographic - establish that many kinds of external representations are used during scientific reasoning: linguistic (descriptions, narratives, written and verbal communications), mathematical equations, visual representations, gestures, physical models, and computational models. Thus even an analysis of *mental* modeling needs to consider the relations among the internal and external representations and processes in problem-solving. Here I consider the question of what might be the nature of the mental representation used in mental modeling such as to enable that internal and external representational coupling during reasoning processes.

The mental models framework

The notion of a "mental model" is central to much of contemporary cognitive science. In 1943, the psychologist and physiologist Kenneth Craik hypothesized that in many instances people reason by carrying out thought experiments on internal models of physical situations, where a model is a structural, behavioral, or functional analog to a real-world phenomenon (Craik, 1943). Craik based his hypothesis on the predictive power of thought and the ability of humans to explore real-world and imaginary situations mentally. We will return to Craik's own view in a later section, after first considering its contemporary legacy. Craik made this proposal at the height of the behaviorist approach in psychology, and so it received little notice. The development of a "cognitive" psychology in the 1960's created a more hospitable environment for investigating and articulating the hypothesis. A new edition of Craik's book with a postscript replying to critics in 1967 fell on more fertile ground and has since had considerable impact on contemporary cognitive science. Since the early 1980's a "mental models framework" has developed in a large segment of cognitive science. This is an explanatory framework that posits models as organized units of mental representation of knowledge employed in various cognitive tasks including reasoning, problem solving, and discourse comprehension.

What is a 'mental model'? How is it represented? What kinds of processing underlie its use? What are the mental mechanisms that create and use mental models? How does mental modeling engage external representations and processes? These issues are not often addressed explicitly in the literature and where they are, there is as yet no consensus position that might serve as a theory of mental models. Thus, I have chosen the word "framework" to characterize a wide range of research. What the positions within this framework share is a general hypothesis that some mental representations of domain knowledge are organized in units containing knowledge of spatio-temporal structure, causal connections and other relational structures.

In the early 1980's several, largely independent, strands of research emerged introducing the theoretical notions of 'mental model' and 'mental modeling' into the cognitive science literature. One strand introduced the notion to explain the effects of semantic information in logical reasoning (Johnson-Laird, 1983). Another strand introduced the notion to explain the empirical findings that in reasoning related to discourse comprehension, people seem to reason from a representation of the structure of a situation rather than from a description of a situation (so-called "discourse" and "situation" models, see Johnson-Laird, 1982; Perrig & Kintsch, 1985). Both of these strands focused on the nature of the representations constructed in working memory during reasoning and problem-solving tasks. Yet another strand introduced the notion in relation to long-term memory representations of knowledge used in understanding and reasoning, in particular, about physical systems. This literature posited the notion to explain a wide range of experimental results indicating that people use organized knowledge structures relating to physical systems in attempting to understand manual control systems and devices in the area of human - machine interactions (see Rouse & Morris, 1986, for an overview) and in employing qualitative domain knowledge of physical systems to solve problems (Gentner & Stevens, 1983).

Some of the early work relating to physical systems that began with psychological studies migrated into AI where computational theories of "naive" or "qualitative" physics in particular were developed to explore issues of knowledge organization, use, access and control, such as in understanding and predicting the behavior of liquids (Hayes, 1979) or the motion of a ball in space and time (Forbus, 1983). Much of the pioneering research in third strand is represented in the edited collection, *Mental Models* (Gentner and Stevens 1983) that appeared in the same year as Johnson-Laird's (1983) monograph of the same name which brought together the working memory strands.

Research within the mental models framework is extensive and varied. As an indication of the range, research includes: AI models of qualitative reasoning about causality in physical systems (see, e.g., Bobrow, 1985), representations of intuitive domain knowledge in various areas, such as physics and astronomy (see, e.g., Vosniadou & Brewer, 1992), analogical problem solving (see, e.g., Gentner & Stevens 1983), deductive and inductive reasoning (see, e.g., Holland, Holyoak, Nisbett, & Thagard, 1986; Johnson-Laird & Byrne, 1993), probabilistic inference (Kahneman & Tversky, 1982), 'heterogeneous' or 'multimodal' reasoning (Allwein & Barwise, 1996), modal logic (Bell & Johnson-Laird, 1998), narrative and discourse comprehension (see, e.g., Johnson-Laird, 1982; Perrig & Kintsch, 1985), scientific thought experimenting (Nersessian, 1991, 1992c), and cultural transmission (Shore, 1997). However, a consensus view has not developed among these areas of research. The preponderance of research into mental models has been concerned with specifying the content and structure of long-term memory models in a specific domain or with respect to specific reasoning tasks or levels of expertise, and not with addressing the more foundational questions raised above. Most importantly, clarification is needed on basic issues as to the nature of the format of the model and the processing involved in using a model.

Given that my focus is on mental modeling during reasoning processes, I consider here only the psychological accounts that hypothesize reasoning as involving the construction and manipulation of a model in working memory during the reasoning process and not with the accounts of the nature of representation in long-term memory, about which my account can remain agnostic. Of course reasoning processes draw on long-term-memory representations and so the account developed of these can lead to insights into the nature of the stored representations that support reasoning and understanding. Additionally in conceptual change, the expectation is that reasoning would lead to changes in the content and structure of long-term memory representations. I also will not address accounts that are primarily computational since, what Rips (1986) pointed out still hold today: computational modeling of qualitative reasoning requires highly complex representations that in the end can do much simpler reasoning than humans can carry out. He considered this a reason for dismissing the very notion of mental modeling, whereas I would counter that the limitations of the computational models stem from the kinds of representations and processing used so far, and that these quite possibly differ from those used by people.

Working memory accounts of mental modeling include those concerned with reasoning and with narrative and discourse comprehension. The literatures on imaginative simulation in mental imagery, mental animation, and perception-based representation also provide insights relevant to developing an account of mental modeling. My strategy is to first address some general issue about representation and processing that we will need in discussing mental modeling, to briefly survey the accounts in the literatures noted, then to propose a synthesis of the several threads in the research to address simulative model-based reasoning as practiced by scientists, and finally to return to the implications of all this for conceptual change.

Format and processing issues

It has been a fundamental presupposition of cognitive science that humans think about real and imaginary worlds though internal representations. Although that assumption has been challenged by researchers in the areas of connectionism, dynamic cognition, and situated cognition, in this section I focus on the controversy about the nature of mental representation as it appears within the traditional cognitive science, where there are mental representations and “internal” and “external” are clear and distinct notions. Recently these founding assumptions were reiterated and elaborated upon by Alonso Vera and Herbert Simon (Vera & Simon, 1993) in response to criticisms. They specify a “physical symbol system” as possessing a memory capable of storing symbols and symbol structures and a set of information processes that form symbols and structures as a function of stimuli, which in humans are sensory stimuli. Sensory stimuli produce symbol structures that cause motor actions which in turn modify symbol structures in memory. Such a physical symbol system interacts with the environment by receiving sensory information from it and converting these into symbol structures in memory and by acting upon it in ways determined by those symbol structures. Perceptual and motor processes connect symbol structures with the environment, thus providing a semantics for the symbols. In the case of humans, then, all representation and processing is internal to the human mind/brain.

What is the nature of the symbols and the symbol structures? Since its inception, there has been a deep divide in the field of cognitive science between those who hold that all mental representation is language-like and those who hold that at least some representation is perceptual or imagistic in format. Herbert Simon reports that this divide “nearly torpedoed the effort of the Sloan Foundation to launch a major program of support for cognitive science” (Simon, 1977, p.385). Volumes of research have since been directed towards and against each side of the divide, and even with significant clarification of the issues and considerable experimental work, the issue remains unresolved and most likely will continue to be until more is known about how the nature of the representation-creating mechanisms in the brain. The format issue is important because different kinds of representation - linguistic, formulaic, imagistic, and analog - enable different kinds of processing operations.

Operations on linguistic and formulaic representations include the familiar operations of logic and mathematics. Linguistic representations, for example, are interpreted as referring to physical objects, structures, processes, or events descriptively. Customarily, the relationship between this kind of representation and what it refers to is truth, and thus the representation is evaluated as being true or false. Constructing these representations requires following a grammar that specifies the proper syntactical structures. Operations on such representations are rule-based and truth-preserving if the symbols are interpreted in a consistent manner and the properties they refer to are stable in that environment. Additional operations can be defined in limited domains provided they are consistent with the constraints that hold in that domain. Manipulation of a linguistic or formulaic representation of a model would require explicit representation of salient parameters including constraints and transition states. Condition - action rules of production systems provide an example, as do the equation-like representations of qualitative process models. In this latter case, simulative reasoning about physical systems occurs by changing the values of variables to create new states of the model. I will call representations with these characteristics “propositional,” following the usual philosophical usage that refers to a language-like encoding possessing a vocabulary, grammar, and semantics (see, e.g., Fodor, 1975) rather than the broader usage sometimes employed in cognitive science which is co-extensive with “symbolic.”

On the other hand, analog models, diagrams, and imagistic representations are interpreted as representing demonstratively. The relationship between this kind of representation, which I will call “iconic,” and what it represents is similarity or goodness of fit (with isomorphism being the limit). Iconic representations are similar in degrees and aspects to what they represent, and are thus evaluated as accurate or inaccurate. Operations on iconic representations involve transformations of the representations that change their properties and relations in ways consistent with the constraints of the domain. Significantly, transformational constraints represented in iconic representations can be implicit, for example, a person can do simple reasoning about what happens when a rod is bent without having an explicit rule, such as “given the same force a longer rod will bend farther.” The form of representation is such as to enable simulations in which the model behaves in accord with constraints that need not be stated explicitly during this process.

Dispersed throughout the cognitive science literature is another distinction pertinent to the format of mental models which concerns the nature of the symbols that constitute propositional and iconic representations - that between “amodal” and “modal” symbols (see, e.g., Barsalou, 1999). Modal symbols are analog representations of the perceptual states from which they are extracted. Amodal symbols are arbitrary transductions from perceptual states, such as those associated with a “language of thought.” A modal symbol representing a cat would retain perceptual aspects of cats; an amodal symbol would have an arbitrary relationship to the cat in the way that, for example, the strings of letters of the words “cat” or “chat” or “Katze” are arbitrarily related to the perceptual aspects of cats. Propositional representations, in the sense discussed above, are composed of amodal symbols. Iconic representations can be composed of either. For example, a representation of the situation “the circle is to the left of the square, which is to the left of the triangle” could be composed of either modal tokens ● - ■ - Δ or amodal tokens, standing for these entities in much the way the letters C - S - T correspond to objects. Whether the mental symbols used in an iconic representation are modal or amodal has implications for how such representations are constructed and manipulated. Constructing a modal representation, for example, is likely to involve reactivation of patterns of neural activity in the perceptual and motor parts of the brain that were activated in the initial experience of something, thus manipulation of the representation is likely to involve perceptual and motor processing, whereas an amodal representation is typically held not to involve sensori-motor processing.

One difficulty in sorting through the mental modeling literature is that one can find all possible flavors in it: propositional, amodal iconic, and modal iconic mental models. Among the working memory accounts, Holland, Holyoak, Nisbett, and Thagard (1986) maintain that reasoning with a mental model is a process of applying condition-action rules to propositional representations of the specific situation, such as making inferences about a feminist bank teller on the basis of a model constructed from representations of feminists and bank tellers. On Johnson-Laird's account mental models are not propositional, rather they are amodal iconic representations. Making a logical inference such as modus ponens occurs by manipulating amodal tokens in a spatial array that captures the salient structural dimensions of the problem and then searching for counterexamples to the model transformation. "Depictive mental models" (Schwartz & Black, 1996a) provide an example of modal iconic mental models. Depictive models are manipulated by using tacit knowledge embedded in constraints to simulate possible behaviors, such as in an analog model of a setup of machine gears. In both instances of iconic models operations on a mental model transform it in ways consistent with the constraints of the system it represents.

Although the jury is still out on the issue of the working memory representations the research that investigates reasoning about physical systems leads in the iconic direction, which, as I will now discuss, was the initial proposal by Craik.

"Craikian" mental modeling

The most influential account of mental modeling is that of Johnson-Laird. On this account, a mental model is an iconic representation that is a structural, behavioral, or functional analog of a real-world or imaginary situation, event, object, or process. Johnson-Laird roots his view in the earlier proposal of Craik; however, his focus has been on mental modeling in the domains of deductive, inductive, and modal logics. This, coupled with his wanting to distinguish mental models from what is customarily understood as mental imagery have led him to underplay or not develop what I see as a central insight of Craik: reasoning about physical systems via mental simulation of analog representations. To account for simulative reasoning about physical systems, and model-based reasoning in science in particular, requires more kinds of model manipulation than logical reasoning, which on Johnson-Laird's account involves moving amodal tokens in spatiotemporal configurations. Tacit and explicit domain knowledge of the physical system, such as causal knowledge, is needed in constructing models and creating new states and inferring outcomes via simulation.

Clearly in the case of science the knowledge required to carry out such a simulation is more complex, but I contend that it is this basic capability that underlies simulative model-based reasoning by scientists. There have been numerous reports by scientists and engineers of conducting mental simulations in solving problems. Kekule claimed to have imagined a circle of snakes, each biting the tale of the snake in front of it, and Einstein claimed to have imagined chasing a beam of light. Roger Shepard (1978) has listed many cases of famous scientists in his discussion of mental imagery. Eugene Ferguson's analysis of the role of visual thinking in engineering visualization and in *Engineering and the Mind's Eye* (Ferguson, 1983) provides several more, most notably Nicola Tesla's report that part of his process of designing devices was to imagine the devices and run them in his imagination over a period of weeks in order to see which parts were most subject to wear. Although the accounts given by historical scientists and engineers are retrospective, there is mounting experimental evidence from mundane and expert studies in support of the hypothesis of reasoning through mental simulation, as will be exemplified below.

The original Craikian notion emphasized the *parallelism* both in form and in operation in internal modeling: "By 'relation - structure' I do not mean some obscure non-physical entity which attends the model, but the fact that it is a physical working model which works in the same way as the process it parallels, in the aspects under consideration at any moment" (Craik, 1943, p. 51). By this I interpret him to mean that the internal model complies with the constraints of the real-world phenomena it represents, not that it is run like a "movie in the head," which signifies vivid and detailed visual representations "running" in real time. Craik based his hypothesis on the need for organisms to be able to predict the environment, thus he saw mental simulation as central to reasoning. He maintained that just as humans create physical models, for example, physical scale models of boats and bridges, to experiment with alternatives, so too the nervous system of humans and other organisms has developed a way to create internal "'small scale model[s]' of external reality" (p.61) for simulating potential outcomes of actions in a physical environment. I interpret his use of quotation marks around "small scale models" to indicate that he meant it figuratively, and not that the brain quite literally creates, for example, an image of small-scale boat whose motion it simulates as in a movie. He does, however, appear to mean that the representations are modal or perception-based. Mental simulation occurs, he claimed, by the "excitation and volley of impulses which parallel the stimuli which occasioned them...." (p.60). Thus the internal processes of reasoning result in conclusions similar to those that "might have been reached by causing the actual physical processes to occur" (p.51). In constructing the hypothesis Craik drew on existing research in neurophysiology and speculated that the ability "to parallel or model external events" (p.51) is fundamental to the brain.

Modern advocates of mental modeling also speculate that the capacity developed for simulating possible ways of maneuvering within the physical environment. It would be highly adaptive to possess the ability to anticipate the environment and potential outcomes of actions, so many organisms should have the capacity for mental simulation. Quite conceivably, then, the rat simulates its path through a familiar maze and performs the appropriate actions to get to the food at the end. Given that modern humans have linguistic capabilities, it should be possible to create mental models from both perception and description, which is borne out by the research on narrative and discourse comprehension that will be discussed below. Additionally, studies of expert/novice reasoning lend support to the possibility that skill in mental modeling develops in the course of learning (Chi, Feltovich, & Glaser, 1981). The nature and richness of models one can construct and one's ability to reason develops in learning domain-specific content and techniques. Thus, facility with mental modeling is a combination of an individual's biology and learning, and develops in interaction with the natural, social, and cultural realities in which one is embedded.

I will next bring together research on discourse and situation models, mental imagery, mental animation, and embodied mental representation as providing evidence in support of a Craikian notion of mental modeling.

Discourse and situation models

Reading, comprehending, and reasoning about stories would seem to epitomize thinking with language. Yet, there is a significant body of cognitive research that supports the hypothesis that the inferences subjects make from these activities are derived through constructing and manipulating a mental model of the situation depicted by the narrative, rather than by applying rules of inference to a system of propositions representing the content of the text. A major strategy of this approach is to differentiate the structure of the text from the structure of the situation depicted in the text and investigate which structure cognitive representations follow. Johnson-Laird in psycholinguistics and others in psychology, formal semantics, and linguistics have proposed cognitive representations in the form of working memory "discourse models" or a “situation models” are used in inferencing related to narratives. On this proposal, the linguistic expressions assist the reader/listener in constructing a mental model through which they understand and reason about the situation depicted by the narrative. That is, in reasoning, the referent of the text would be an internal model of the situation depicted by the text rather than a description. The central idea is that “discourse models make explicit the structure not of sentences but of situations as we perceive or imagine them" (Johnson-Laird, 1989, p.471). The principal tenets of the theory, as outlined by Johnson-Laird, are as follows. As a form of mental model, a discourse model would embody a representation of the spatial, temporal, and causal relationships among the events and entities of the situation described by the narrative. In constructing and updating a model, the reader calls upon a combination of pre-existing conceptual and real-world knowledge and employs the tacit and recursive inferencing mechanisms of her cognitive apparatus to integrate the information with that contained in the narrative. In principle these should be able to generate the set of all possible situations a narrative could describe.

A number of experiments have been conducted to investigate the hypothesis that in understanding a narrative readers spontaneously construct mental models to represent and reason about the situations depicted by the text (Dijk & Kintsch, 1983; Franklin & Tversky, 1990; Johnson-Laird, 1983; Mani & Johnson-Laird, 1982; McNamara & Sternberg, 1983; Morrow, Bower, & Greenspan, 1989; Perrig & Kintsch, 1985; Zwann, 1999; Zwann & Radvansky, 1998). Although no instructions were given to imagine or picture the situations, when queried about how they had made inferences in response to an experimenter's questioning, most participants reported that it was by means of "seeing" or "being in the situation" depicted. That is, the reader sees herself as an "observer" of a simulated situation. Whether the view of the situation is "spatial", i.e., a global perspective, or "perspectival", i.e., from a specific point of view, is still a point of debate, though recent investigations tend to support the perspectival account, that is, the reference frame of the space appears to be that of the body (Bryant & Tversky, 1999; Glenberg, 1997b; Mainwaring, Tversky, & Schiano, 1996).

The interpretation given these experimental outcomes is that a situation represented by a mental model could allow the reasoner to generate inferences without having to carry out the extensive operations needed to process the same amount of background information to make inferences from an argument in propositional form. The situational constraints of the narrative are built into the model, making many consequences implicit that would require considerable inferential work in propositional form. For example, consider a case where a subject is asked to move an object depicted in a model. Moving an object changes, immediately, its spatial relationships to all the other objects. In simulative mental modeling, the reasoner could grasp this simply by means of the changes in the model and not need to make additional inferences. Such reasoning should be discernibly faster. Thus, the chronometric studies noted above provide additional experimental support that making inferences through simulation is faster than making logical inferences from propositions. Finally, reasoning through a model of a situation should restrict the scope of the conclusions drawn. For example, moving an object in a specified manner both limits and makes immediately evident the relevant consequences of that move for other objects in the situation detailed by the narrative. Further support is thus provided by demonstrations in this literature that it is much more difficult to make inferences - and sometimes they are not made at all - when participants are required to reason with the situation represented in propositional form.

Mental spatial simulation

There is an extensive literature that provides evidence that humans can perform various simulative transformations in imagination that mimic physical spatial transformations. The literature on mental imagery establishes that people can mentally simulate combinations, such as with the classic example where subjects are asked to imagine a letter B rotated 90 degrees to the left, place an upside triangle below it and remove the connecting line and the processes produces an image of a heart. People can perform imaginative rotations that exhibit latencies consistent with actually turning a mental figure around, such as when queried as to whether two objects presented from different rotations are of the same object (Finke, 1989; Finke, Pinker, & Farah, 1989; Finke & Shepard, 1986; Kosslyn, 1980, 1994; Shepard & Cooper, 1982; Tye, 1991), and there is a correlation between the time it takes participants to respond and the number of degrees of rotation required. Further, rotational transformations of plane figures and 3-dimensional models are evidenced. As Stephen Kosslyn (1994, p. 345) summarizes, psychological research provides evidence of rotating, translating, bending, scaling folding, zooming, and flipping of images. The combinations and transformations in mental imagery are hypothesized to take place according to internalized constraints assimilated during perception (Shepard, 1988). Kosslyn also notes that these mental transformations are often accompanied by twisting and moving one's hands to represent rotation, which indicates motor as well as visual processing (see also Jeannerod, 1993, 1994; Parsons, 1994). Other research indicates that people combine various kinds of knowledge of physical situations with imaginary transformations, including real-time dynamical information (Freyd, 1987). When given a problem about objects that are separated by a wall, for instance, the spatial transformations exhibit latencies consistent with the participants having simulated moving around the wall rather than through it, which indicates at least tacit use of physical knowledge that objects cannot move through a wall (Morrow, Bower, & Greenspan, 1989). This kind of knowledge is evidenced in other studies, such as those in which participants are shown a picture of a person with an arm in front of the body and then one with the arm in back, and they report imagining rotating the arm around the body, rather than through it, and the chronometric measurements are consistent with this (Shiffrar & Freyd, 1990).

Although physical knowledge other than spatial appears to be playing a role in such imaginings, it has not been explored systematically in the mental imagery literature. The kinds of transformations considered thus far are spatial:

structural/geometrical/topological transformations. I refer to the literature on imagery not to make the claim that mental models are like images, but because this literature provides significant evidence for the hypothesis that the human cognitive system is capable of transformative processing in which spatial transformations are made on iconic representations through perceptual and motor processes. Indeed, there is significant evidence from neuropsychology that the perceptual system plays a role in imaginative thinking (see, e.g., Farah, 1988; Kosslyn, 1994). Again, this makes sense from an evolutionary perspective. The visual cortex is one of the oldest and most highly developed regions of the brain. As Roger Shepard, a psychologist who has done extensive research on visual cognition, has put it, perceptual mechanisms "have, through evolutionary eons, deeply internalized an intuitive wisdom about the way things transform in the world. Because this wisdom is embodied in a perceptual system that antedates, by far, the emergence of language and mathematics, imagination is more akin to visualizing than to talking or to calculating to oneself" (Shepard, 1988, p.180). Although the original ability to envision, predict, and inference by imagining developed as a way of simulating possible courses of action in the world, as humans developed, this ability has been "bent to the service of creative thought" (*ibid*.). Understood in this way, the mundane ability to imagine and visualize underlies some of the most sophisticated forms of human reasoning as evidenced in creative reasoning in science. To stress once again, though, the representational format of mental imagery should not be conflated with that of external pictorial representations. As various researchers have shown, such as with Gestalt figures (Chambers & Reisberg, 1985), internal representations appear sketchier and less flexible in attempts at reinterpretation. Furthermore, congenitally blind individuals can carry out some classic imagery tasks, though the source of such transformational knowledge would be haptic perception and the imagery possibly kinesthetic in nature (Arditi, Holtzman, & Kosslyn, 1988; Kerr, 1983; Marmor & Zaback, 1976).

Mental animation

There is a growing literature in psychology and neuroscience that investigates the hypothesis that the human cognitive system possesses the ability for *mental animation* in problem solving tasks. This ability would be central in Craikian mental modeling. This kind of simulative model-based reasoning both in mundane thinking and in science is likely to go beyond just making spatial transformations and extend to the kinds of transformations of physical systems requiring causal and other behavioral knowledge. Indeed, Shepard extended his claim about the nature of the information humans internalize about how things transform in the world to include behavioral constraints, and attempted to develop an account of the psychokinetic laws of such transformations (Shepard, 1984, 1994). There is also a significant body of research on infant cognition that has established that days old infants have an acute sensitivity to causal information. Infants gaze longer and show more interest in events that appear to contradict causality (Spelke, 1991; Spelke, Phillips, & Woodward, 1995).

Recent investigations of physical reasoning have moved beyond spatial and temporal transformations to examining the role of causal and behavioral knowledge in mental simulation. The ability to mentally animate is highly correlated with scores on tests of spatial ability (Hegarty & Sims, 1994). However, as Mary Hegarty, too, stresses the mental representations underlying animation need not be what are customarily thought of as “mental images.” Images are often taken to be vivid and detailed holistic representations, such as in a photograph or in a movie, where simulation would take place all at once. However, the imagery literature supports the notion that imagery most often is largely sketchy and schematic and that animation of an image can be piecemeal, as supported by her research. Kosslyn’s highly elaborated neuroscience account of imagery (Kosslyn, 1994), argues that transformations of the image most likely take place outside of the visual buffer through connections with long term memory representations, with the image in the buffer being “refreshed” with the updated transformation.

Much of this research has its origin in thinking about diagrammatic representations in reasoning, specifically, inferring motion from static representations. It thus provides insights into the relations between internal and external representations that we will follow up on in a later section. One indication of interaction is that participants in these kinds of studies often use gestures, sometimes performed over the diagram, that simulate and track the motion (see, e.g., Clement, 1994, 2003; Golden-Meadow, Nusbaum, Kelly, & Wagner, 2001; Hegarty & Steinhoff, 1994). Prominent research on mental animation includes Hegarty's (Hegarty, 1992; Hegarty & Ferguson, 1993; Hegarty & Just, 1989) investigations of reasoning about the behavior of pulley systems and Daniel Schwartz's (Schwartz, 1995; Schwartz & Black, 1996a, 1996b) studies focusing on gear rotations. These studies, respectively, provide evidence that people are able to perform simulative causal transformations of static figures provided of the initial set up of the pulleys and of the gears. Several findings are important here. Protocols of participants indicate that they do not mentally animate the pulley systems all at once as would appear to happen in the real world experience of it, but animate in segments in the causal sequence, working out in a piecemeal fashion the consequences of previous motion for the next segment. The response time for the participants in the gear problems indicates they, too, are animated in sequence, and when given only one set of gears, participants response time was proportional to the rate of the angle of rotation. Participants perform better when given more realistic representations of gears, than highly schematic ones, such as those of just circles with no cogs. In the realistic case they seem to use physical knowledge, such as friction, directly to animate the model, whereas in the schematic case they revert to more analytic strategies such as comparing the size of the angles that gears of different sizes would move through. Schwartz's research also indicates that mental animation can make use of other non-visual information such as of viscosity and gravity. When participants are well trained in rules for inferring motion, however, they often revert to these to solve the problem more quickly (Schwartz & Black, 1996). Mental animation, on the other hand, can result in correct inferences in cases where the participant cannot produce a correct description of the animation (Hegarty, 1992). Further, people can judge whether an animation is correct even in cases where the self-produced inference about motion is incorrect (Hegarty, 1992).

Although not much research has been conducted with scientists, what there is indicates that they, too, "run" mental models in problem solving (Clement, 1994; Trafton, Trickett, & Mintz, in press). As with the gear and pulley studies, that research provides evidence of significant interaction between the internal and external representations in the mental simulation. Though it is some distance from employing causal transformations of rotating gears or pulleys to employing the kinds of transformations requiring knowledge contained in a scientific theory, the mental animation research supports the position that the scientific practices originate in and develop out of mundane imaginative simulation abilities.

Internal - external coupling

As noted previously, mental modeling is often carried out in the presence of real-world resources, including representations such as diagrams and objects such as sofas. How might the mental capability interface with relevant resources in the external world? Much of the research on this question is directed towards diagrams and other kinds of visual representations. Research by Jiajie Zhang (Zhang, 1997; Zhang & Norman, 1995), for instance, analyzes diagrams as external representations that are coupled as an information source with the individual solving problems. Recently, Hegarty has argued that the corpus of research on mental animation in the context of visual representations leads to the conclusion that internal and external representations are best seen as forming a "coupled system" (Hegarty, 2005). In considering the relation between mental modeling and external physical models I have argued that we need to conceptualize cognitive capacities as encompassing more than "natural" biological capacities (Nersessian, 2002a). "Cognitive capacities" can encompass various kinds of external representations such as text, visual representations, and physical simulation devices, such as those evidenced in ethnographic research on cognitive practices in biomedical engineering where technological artifacts instantiate models of *in vivo* phenomena to carry out *in vitro* simulations (Nersessian, 2005; Nersessian, Kurz-Milcke, Newstetter, & Davies, 2003).

On the traditional cognitive science view, reasoning uses information abstracted from the external environment and represented internally and processed internally. External displays or various sorts of information in the world might assist working memory by, for example, co-locating information that gets abstracted (Larkin, 1989; Larkin & Simon, 1987), but all cognitive processing is internal to the individual mind. The traditional view is under challenge by several current research strands that re-construe the notion of representation and processing such that some information remains in the environment and that processing is within the coupled system linking internal and external worlds. A major open problem for the coupled system view is an account of the nature of the cognitive mechanisms through which the internal and external worlds mesh, and this is an empirical question. On the one hand, given that some mental simulation can take place in the absence of external stimuli, the mechanisms need to be such as to take stored information and process it in such a way as to allow for the possibility of making at least some of the same inferences as if the real-world stimuli were present. On the other hand, as Daniel Dennett has noted succinctly, "[j]ust as you cannot do very much carpentry with your bare hands, there's not much thinking you can do with your bare mind" (Dennett, 2000, p.17). Thus, even in the absence of an account of "mechanisms," there has been considerable theorizing over the last twenty years in the direction of how aspects of the environment might enter directly into cognitive processes, rather than simply scaffolding them.

"Environmental perspectives" (Nersessian, 2005) make human action the focal point for understanding cognition and emphasize that cognition occurs in complex social, cultural, and material environments. Although not all strands of research contributing to these perspectives have taken the system view of cognition, each can be considered as contributing support for the argument in its favor. This research comprises the notions that cognition is "embodied" (perception-based accounts of representation such as Barsalou, 1999; Glenberg & Langston, 1992; Glenberg, 1997; Johnson, 1987; Lakoff, 1987; Lakoff & Johnson, 1998); "enculturated" (co-evolution of cognition and culture such as Donald, 1991; Nisbett, Peng, Choi, & Norenzayan, 2001; Shore, 1997; Tomasello, 1999)); "distributed" (occurring across systems of humans and artifacts such as Hutchins, 1995; Norman, 1988; Zhang & Norman, 1995; Zhang, 1997)), or "situated" (located in and arising from interactions within situations such as Clancey, 1997; Greeno, 1989, 1998; Lave, 1988; Suchman, 1987).

One mantra of the distributed and situated research is that cognition is not only "in the mind" or "in the world" but "in the system" such that an individual's mental activities comprise interactions with other material and informational systems (including other humans). To accommodate this insight, the distributed cognition perspective proposes analyses of cognitive processing that incorporate the *salient* resources in the environment in a non-reductive fashion (see, e.g., Hutchins, 1995a, 1995b; Norman, 1991). Salient resources are, broadly characterized, those factors in the environment that can affect the outcome of a cognitive activity, such as problem solving. These cannot be determined *a priori* but need to be judged with respect to the instance. For ship navigators, for example, the function of a specific instrument would be salient to piloting the ship, but not usually the material from which the instrument is made. For physicists, whether one sketches on a black board or white board or piece of paper is likely irrelevant to solving a problem, but sketching on a computer screen has the potential to be salient because the computer adds resources that can affect the outcome.

The artifacts of a culture that participate in systems that perform cognitive functions are referred to as "*cognitive artifacts"* and determining these within a specific system is a major part of the analytical task for environmentalists. Hutchins has studied the cognitive contributions of artifacts employed in modern navigation, such as the alidade, gyrocompass, and fathometer. Various kinds of external representations are candidate cognitive artifacts, and much research has focused on visual representations, especially diagrams. In addition to the mental animation literature discussed above, there is an extensive literature on diagrammatic representations that reinforces the "coupled system" notion, such as that of Zhang and Norman referenced earlier (Zhang & Norman, 1995). They have studied problem solving with isomorphic problems to ascertain potential cognitive functions of different kinds of visual representations and have found that external representations differentially facilitate and constrain reasoning processes. The format of the external representation, for example, can change the nature of the processing task, as when the tic-tac-toe grid is imposed on the mathematical problem of "15". Specifically, they argue that diagrams can play more than just a supportive role in what is essentially an internal process; rather, these external representations can be coupled directly as an information source with the person without requiring the mediation of an internal representation of the information provided in them. Not all external representations are equally facilitating, though, as Malcom Bauer and Johnson-Laird (Bauer & Johnson-Laird, 1993) show in their study of diagrams in mental modeling tasks. Intriguingly, diagrams with information represented in amodal iconic format appear to provide no facilitation, but diagrams in modal format - perceptually resembling the objects being reasoned about - do significantly enhance problem solving, as was evidenced also in the mental animation research.

In research on problem solving with diagrammatic representations in formal logic Keith Stenning and colleagues have argued that they restrict the internal problem space so as to constrain the kinds of inferences that can be made (Stenning, 2002; Stenning & Oberlander, 1995). Recently, Trafton and colleagues (Trafton, Trickett, & Mintz, in press) have been investigating scientist's interactions with computer visualizations, which offer more and greater ease of possibilities for manipulation during problem solving. They have found that in the presence of external computer visualizations, scientists tend to do considerable mental manipulation interactive with the visualization represented before them, instead of either just creating a mental image or making direct adjustments to the image on the computer screen. Their manipulations and comparisons seemed to be aimed at constructing a mental model constrained by the computer visualization and through which to understand the implications of the visualization.

The ethnographic studies my research group has been conducting examine the role of representations in the form of physical devices used by biomedical engineers for simulating *in vivo* biological processes. Within the cognitive systems in the laboratory these physical devices instantiate part of the current community model of the phenomena and allow simulation and manipulation of this understanding. One researcher aptly referred to the process of constructing and manipulating these *in vitro* physical models as "putting a thought into the bench top and seeing whether it works or not." These instantiated "thoughts" allow researchers to perform controlled simulations of an *in vivo* context, for example, of the local forces at work in the artery. We interpret such simulative model-based reasoning as a process of co-constructing and manipulating the “internal” researcher models of the phenomena and of the device and the ‘external’ model that is the device, each incomplete. Here simulative model-based reasoning consists of processing information both in memory and in the environment (see also Gorman, 1997; Greeno, 1989). Although the capacity for making inferences might be ascribed to the traditionally conceived “mental” part, the internal and external representations and processes involved in simulative model-based reasoning are best understood as a coupled system, and thus the ascription of “mental” might better be construed as pertaining more to the property that inferences are generated from it than to it as a locus or medium of operation. Components of the inferential system would include both one or more people and artifacts (Osbeck & Nersessian, 2006). For simplicity, here, I will continue to use “mental modeling” as referring to the human locus of operation.

One way to accommodate the hypothesis of coupling between external and internal representations is to expand the notion of memory to encompass external representations and cues; that is, to construe specific kinds of affordances and constraints in the environment, literally, as memory in cognitive processing. If memory is so distributed, then we can conceive of the *problem space* not in the traditional way as internally represented, but as comprising internal and external resources (Nersessian, 2005; Nersessian, Kurz-Milcke, Newstetter, & Davies, 2003; Nersessian, Newstetter, Kurz-Milcke, & Davies, 2002). The evolutionary psychologist Merlin Donald (Donald, 1991) has argued that evolutionary considerations lead to the view that human memory encompasses internal and external representation. Donald uses a wide range of evidence from anthropology, archeology, primatology, and neuroscience to argue his case. He maintains that this evidence establishes that external representations have been and continue to be indispensable in complex human thinking, and their development was central to the processes of cultural transmission. Donald's analysis of the evolutionary emergence of distinctively human representational systems starts from the significance of mimesis - or re-creation such as using the body to represent an idea of the motion of an airplane - in the developments of such external representations as painting and drawing (40K years ago), writing (6K), and phonetic alphabets (4K). The artifacts that contribute to remembering are social and cultural constructs designed by human communities that rely on them in supporting remembering. Donald argues for a distributed notion of memory as a symbiosis of internal and external representation on the basis of changes in the visuo-spatial architecture of human cognition that came about with the development of external representation. On this notion affordances and constraints in the environment are *ab initio* part of cognitive processing.

Recasting cognition such that the relationship between the internal and external worlds form a coupled cognitive-cultural system, presents the challenge for cognitive science to determine the mechanisms of representation and processing that would enable this coupling. Part of this problem is to address format and processing issues with respect to the human components of the system. Here Greeno's criteria that the internal representations in mental modeling processes to be such that "we interact with them in ways that are similar to our interactions with physical and - probably - social environments," (Greeno, 1989, p. 313) and thus be such that they are "acquired with significant properties of external situations and one's interactions with the situations ....such that at least some of the properties are known implicitly in something like the way that we know how to interact with [external] environments" (p. 314) echo the earlier views of Craik, as do the analyses of Shepard (Shepard, 1984, 1988, 1994) on the internalization of physical constraints. Human representations need also to be such that they interface smoothly with other system representations in problem solving processes. One plausible way for the interfacing to be smooth is for human representations to have modal aspects such that perceptual and motor mechanisms would be employed in processing.

Embodied representation: "Perceptual" mental models

What might the format of the representation of a "Craikian" mental model be? For Johnson-Laird's analysis of logical reasoning, the working memory constructs are iconic representations. Perhaps for logical reasoning it suffices that the information in a mental model is represented amodally. Model-based reasoning about physical systems, however, needs to allow for the possibility of simulations of physical entities, situations, and processes that go beyond manipulating amodal tokens in a spatial array. Following Craik's notion of parallelism in the form and operation of internal modeling used in reasoning, working memory models of physical systems would be perception-based representations. Considerable knowledge would be needed to carry out such a mental simulation, not just what can be derived from perception as it is usually understood as separate from conceptual understanding. The behaviors of the parts of the model, for example, need to be connected to knowledge of how these function, although much of this can be tacit. For example, people can usually infer how water will spill out of a cup without being able to make explicit or describe the requisite knowledge. Although we have only been considering mental modeling as a working memory process, of course information from long term memory plays a role in this process, some of which is likely to be represented in propositional form. Thus, as with mental imagery (Kosslyn, 1994), mental modeling representations need to maintain a connection to long-term memory representations, and so an account is needed of how information might be stored so as to connect to working memory representations.

It is a common sense observation *that* humans do have some means of storing knowledge and of calling it selectively into use, but the format of that information remains an open question. What I want to accomplish in this section is to draw on research on *embodied* representations to propose that the format of the information contained in working memory representation is modal and most likely also the information to which the models are connected in memory that enable simulation has a modal aspect. This would be the most efficient way for the internal - external representational coupling to work. The embodied representation research focuses on the implications of the interaction of the human perceptual system with the environment for internal representation and processing, generally. Proponents contend that a wide range of empirical evidence shows perceptual content is retained in all kinds of mental representations, and that perceptual and motor mechanisms of the brain play a significant role in many kinds of cognitive processing traditionally conceived as separate from these, including memory, conceptual processing, and language comprehension (see, e.g., Barsalou, 1999, 2003; Barsalou, Simmons, Barbey, & Wilson, 2003; Barsalou, Solomon, & Wu, 1999; Catrambone, Craig, & Nersessian, 2005; Craig, Nersessian, & Catrambone, 2002; Glenberg, 1997b; Johnson, 1987; Kosslyn, 1994; Lakoff, 1987; Solomon & Barsalou, 2004; Yeh & Barsalou, 1996).

One extensive area of research concerns the representation of spatial information in mental models. This research leads to the conclusion that internal representation of spatial configurations does not provide an "outsider" 3-D Euclidian perspective - the "view from nowhere" - but provides an embodied representation that is relative to the orientation of one's body and to gravity. In early research Irwin Rock hypothesized that there is a “deeply ingrained tendency to ‘project’ egocentric up-down, left-right coordinates onto the [imagined] scene” (Rock, 1973, p. 17). This hypothesis is borne out by recent research (see, e.g., Bryant & Tversky, 1999; Bryant, Tversky, & Franklin, 1992; Franklin & Tversky, 1990; Glenberg, 1997a; Perrig & Kintsch, 1985). In particular, Barbara Tverksy and colleagues have found that mental spatial alignment corresponds with bodily symmetry - up-down, front-back, and gravity - depending on how the participant is oriented in the external environment. When asked to imagine objects surrounding an external central object, mental model alignment depends on whether the object had the same orientation as the observer. Arthur Glenberg argues that this bodily orientation is tied to preparation for *situated action* paralleling that which would occur in real-world situations (Glenberg, 1997).

A second line of research focuses on concept representation. From an embodied cognition alternative, as expressed by George Lakoff and Mark Johnson, a “concept is a neural structure that is actually part of, or makes use of, the sensorimotor system of our brains” (Lakoff & Johnson, 1998, p. 20). Lawrence Barsalou has been formulating a theory (first fully articulated in Barsalou, 1999) of the human conceptual system that calls into question the traditional understanding of concept representation as amodal. A wide range of research dovetails in thinking about embodiment and representation, but I will focus largely on the recent work of Barsalou and colleagues because they argue for the perceptual basis of concept representation through drawing together evidence from much of that research, as well as through experiments specifically designed to test the hypothesis. Since my goal is not to argue that Barsalou's theory is "right" - but rather to advocate that it goes in the right direction for further articulating the kind of account of simulative model-based reasoning the science case requires - I present only the broad outlines.

Barsalou argues that there is an extensive experimental literature that can be read as supporting the contention that mental representations retain perceptual features, or are modal, and that many cognitive functions involve re-enactment or "simulation" of perceptual states. These include perceptual processing, memory, language, categorization and inference. He makes a compelling experimental case for the broad claims of the theory from evidence drawn from existing behavioral and neuroscience research, and behavioral tasks designed specifically to test its implications (as summarized in Barsalou, 2003). The experiments he and his colleagues have designed to test the implications of the theory primarily involve property generation and property verification tasks. They distinguish between the alternatives of simulating the referent of a word (modal version) and looking up a word in a semantic network or frame (amodal version). The participants are given either a neutral condition with no instructions on how to do the task or an imagery condition where they are asked to visualize or imagine the referent. On the amodal version, the neutral condition should produce patterns of response different from the imagery condition. Across a wide range of terms, these experiments show a similar pattern of responses between the two conditions, favoring the modal version. Other significant experiments involve manipulating perceptual variables, such as occlusion. For example, in property generation experiments, participants listed twice as many internal features of objects when they were presented with modified object terms such a "rolled up lawn" (e.g., "roots") as opposed to "lawn," ½ watermelon (e.g., "seeds"), and glass car (e.g., "seats") (Barsalou, Simmons, Barbey, & Wilson, 2003; Barsalou, Solomon, &Wu, 1999). Experiments using fMRI in the neutral condition provide evidence of activity in sensorimotor areas of the brain during the property generation task, whereas on the traditional separation of cognition and perception (amodal version), there should be no activation in sensorimotor areas when representing a concept (Simmons, Hamann, Nolan, Hu, & Barsalou, 2004).

On Barsalou's modal account, cognitive processing employs "perceptual symbols" ("modal iconic" representations on our earlier classification), which are neural correlates of sensorimotor experiences (Barsalou, 1999). These symbols "result from an extraction process that selects some subset of a perceptual state and stores it as a symbol" (Barsalou & Prinz, 1997, p. 275). The relationship between the symbols and what they represent is analogical, i.e., that of similarity, as opposed to arbitrary. The perceptual symbols form a common representational system that underlies both sensorimotor and conceptual processing. Because the conceptual system uses perceptual and motor mechanisms, concept representations are distributed across modality specific systems. These representations possess simulation capabilities; that is, perceptual and motor processes associated with the original experiences are re-enacted when perceptual symbols are employed in thinking. Concepts are separable neural states underlying perception and constituting the units of long-term memory representation, which in turn can be organized into knowledge units such as schemas, mental models, or frames.

Coupling among various representations takes place in categorization processes, including the construction of ad hoc categories, to form "perceptual symbol systems." One strong objection against perceptual representations has been that they cannot accommodate properties known to hold of conceptual systems, such as the potential to produce an infinite number of conceptual combinations and the capability to distinguish types from tokens and to represent abstract concepts. The need to accommodate these known possibilities of conceptual representations led to the traditional propositional (amodal) account, rather than direct empirical evidence in favor of it. However, there are several notorious problems with the amodal account, including the "symbol grounding problem," that is, the problem of how are the arbitrary transductions mapped back onto perceptual states and entities in the world (Harnard, 1990; Searle, 1980). Barsalou (1999) and, later, Jesse Prinz (Prinz, 2002) provide arguments that, in principle, perceptual symbol systems can exhibit all the salient characteristics of propositional systems. The (mis-)perception that they cannot stems from the tendency to conflate perceptual representations with *recording systems* in which images are captured but are not interpreted (Haugeland, 1991). The human conceptual system is interpretive and inferential. Perceptual symbols are not holistic representations of their real-world counterparts and their componential, schematic, and dynamic nature allows for combination, recombination, and abstraction. Barsalou stresses that the human conceptual system should not be understood by means of an analogy to a recording system. Perceptual symbols are schematic extractions from perceptual processes that allow for infinite possibilities of imaginative recombination. Further, one should not expect simulations to be as detailed or vivid as the original perceptions. In conducting a perceptual simulation, one needs neither to be consciously aware of mental imagery, which requires extra cognitive effort to produce, or of the simulation process. Performing a perceptual simulation is not akin to "running" a kind of motion picture in the head.

Concept representation is likely to have both modal and amodal aspects. However, the modal aspects serve the requirements of simulative mental modeling we have been discussing - both the simulation needs and the need for interfacing between external and internal representations. There are many open questions about modal representation for which only partial solutions have been suggested, such as: how do abstract concepts become represented? how does "translation" take place across modalities? how does integration take place? how are perceptually dissimilar instances of a concept recognized and categorized? But there are many open questions about amodal representation as well, and, significantly, as Barsalou points out, there is little direct empirical evidence in favor of a fully amodal view. In sum, Barsalou and other proponents of embodied cognition do make a compelling case that at the very least a more tempered conclusion is warranted in the present circumstances, and this is sufficient for our needs: "The conceptual system appears neither fully modular nor fully amodal. To the contrary, it is non-modular in sharing many important mechanisms with perception and action. Additionally it traffics heavily in the modal representations that arise in sensory-motor systems" (Barsalou, 2003, p.27). Thus, how modal representations could contribute to various cognitive processes, such as mental modeling, merits investigation.

A "perceptual mental model" (which I want Craik seems to have in mind) would facilitate the interfacing between the internal and external representations of a coupled system in simulative reasoning. Recall that on Craik's speculation, mental simulation occurs by the "excitation and volley of impulses which parallel the stimuli which occasioned them...." (Craik, 1943, p.60), with simulative reasoning processes resulting in conclusions similar to those that "might have been reached by causing the actual physical processes to occur" (p.51). On the

people should be able to interact with the internal representations "in ways that are similar to our interactions with physical and - probably - social environments" (Greeno, 1989, p.313). Perceptual mental models are built on representations "acquired with significant properties of external situations and one's interactions with the situations ....such that at least some of the properties are known implicitly in something like the way that we know how to interact with [external] environments" (p. 314). So, affordances and constraints of situational information would be at play even in the solely imaginative cases of mental modeling where only one's conceptual understanding is used. Just how the mental models would be "run" in simulative reasoning is an open research question requiring more knowledge about the cognitive and neural mechanisms underlying such processes. But it cannot be assumed *a priori* that these reduce to the same kinds of computations possible for a computer. And, even if deductive and inductive reasoning were to use amodal representations, it is possible that simulative reasoning about physical systems could involve modal representations and perceptual - motor processes, enabling direct and effective use of affordances and constraints of representations external to humans in the system. The mental model and the real-world resources form a coupled system by which inferences are made. In this way the problem solver does not simply "use" external representations, rather they are incorporated directly into the *cognitive* processing.

Conclusion: Model-based reasoning in conceptual change in science

I have argued here that the capacity for mental modeling provides a cognitive basis for model-based reasoning evidenced in conceptual changes in the sciences. It is a fundamental form of human reasoning that is likely to have evolved as an efficient means of navigating the environment, of anticipating situations, and of solving problems in matters of significance to existence. Humans have extended its use to more esoteric situations, such as constructing and reasoning with scientific representations. A mental model is a conceptual system representing the physical system that is being reasoned about. It is an abstraction - idealized and schematic in nature - that represents a physical situation by having surrogate objects or entities and properties, relations, behaviors, or functions of these that are in correspondence with it. In mundane reasoning situations, mental models are likely homomorphic (many-one), but in scientific reasoning, the intended relation is isomorphic (one-to-one with respect to salient dimensions). Mental models embody and comply with the constraints of the phenomena being reasoned about, and enable inferences about these through simulation processes. Inferences made in simulation processes create new data that play a role in evaluating and adapting models. In reasoning processes, mental models interact with other representations - external diagrams, written equations, verbal representations such as written or oral descriptions or instructions, and gestural representations provide examples of these. The notion of interaction among internal and external resources during reasoning as "representational coupling" leads to the notion that mental models have significant modal aspects ("perceptual mental models"), though a conclusive argument cannot be made in either the modal or amodal literatures.

Simulative mental modeling can lead to potential empirical insights, as in thought experimenting (Nersessian, 1992b), by creating new states or situations that parallel those of the real world. In mundane cases at least tacit knowledge of constraints is needed, such as that the chair cannot simply pass through the wood of the door frame or that the frame of the sofa will not bend or be capable of squishing as does a cushion. In the case of science, implicit and explicit knowledge of constraints relating to general principles of the domain and mathematical equations play a role. This knowledge such as of causal coherence and mathematical consistency is likely to be represented in different informational formats. A cognitive science account is still needed of how conceptual, and in general, domain knowledge is utilized in mental modeling, how abstraction and model construction take place, and how the mental processes interface with the external world.

How might reasoning through mental modeling lead to conceptual change? A central problem is that given that conceptual innovation starts from existing representations, how is possible for a genuinely novel representation to be created? In earlier work I have proposed that a significant method of conceptual innovation and change in science involves iterative processes of constructing, evaluating, and revising models that exemplify features of the phenomena under investigation. These models do not serve simply as aids to reasoning but are the means through which one reasons to the new conceptual representations. The model construction and manipulation processes, which include analogical, imagistic, and simulative processes, abstract and integrate information from multiple sources specific to the problem-solving situation so as to allow for truly novel combinations to occur, that is, for a model in which heretofore unrepresented structures or behaviors emerge. The consequences of the novel combinations can be explored imaginatively, through physical realizations, and through manipulations possible by expression in other representational formats, such as mathematics and language. Selective abstraction is needed for this kind of representation building. Take, for example, the case of Maxwell's construction of the field representation of electromagnetism. In using continuum mechanics as an analogical source domain, he was able to narrow the source further to that of elastic fluids by guiding the selection with constraints from the electromagnetic target domain. The selection of relevant structures from the domain of elastic fluids was in turn guided by the constraints that a model would need to be capable of rotational motion (creating "vortices") and result in certain kinds of geometric configurations so as to give rise to observed lines of force, and thus the resulting model was a hybrid of constraints from both domains. Such hybrid representations possess their own, emergent, constraints that figure into the analytical mix. Maxwell's initial hybrid model, for instance, led to the constraint of friction between vortices when in motion. It is likely that he recognized the friction constraint though attempting to simulate the model imaginatively. In such a simulation one could see the vortices touching and infer friction between them. Following out the problem of accommodating the model constraint of friction led him to another source domain, machine mechanics, a new representational resource, the "idle-wheel," and then another hybrid model which proved capable of representing additional electromagnetic constraints as well as possessing emergent constraints.

Many abstractive processes enable model construction, including, idealization, limiting case, and generic abstraction. These provide ways of generating and accommodating constraints from multiple domains. "Generic" abstraction, for instance, captures the idea that in reasoning it is possible to make inferences not only about the specific model, but also about the class of models at different levels of abstraction, for example, reasoning about a specific spring or reasoning about it as representative of the class of simple harmonic oscillators. The Maxwell case provides an exemplar of what is powerful about this mode of abstractive reasoning. Starting from thinking about specific connecting mechanisms, such as idle wheels, and abstracting to what the dynamical relations between idle wheels and vortices have in common with the category of "general dynamics of relational structures that capture the motion of a connected system in which one part imparts motion to another in a continuous fashion," Maxwell arrived at a continuous-action representation of the transmission of forces, that is, a concept of "field" - a heretofore unrepresented structure in physics.

Finally, a significant way in which conceptual change in science is unlike that in learning and cognitive development is that it occurs also across communities. The community of physicists, for instance, experiences a conceptual change from understanding "force" to represent actions-at-a-distance to representing continuous-action in the space surrounding charges and bodies and through the space between them or understanding "mass" to represent an invariant quantity to understanding it to represent something that varies with speed. Most philosophical and sociological explanations of conceptual change operate at the level of how scientists choose among alternative conceptual structures or how one structure comes to replace another in a community. Thomas Kuhn, for example, in his post-*Structure* writings repudiated his "gestalt switch" metaphor as characterizing conceptual change for precisely the reason that he argued that he intended to be addressing the level of community change while the metaphor operates at the level of individuals. However, for there to be a community phenomenon, a story needs to be told at the individual level as well (Kuhn was likely also addressing this in his last work on the unfinished follow-on book to *Structure*). That is, what is the nature of cognitive processes used by individual scientists that generate new concepts and conceptual structures, making them available for communities to choose among, if that is what happens in the community? It is this story that has the potential to contribute to accounts of conceptual change in learning and in cognitive development.

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