2

Interpreting Scientific and Engineering Practices: Integrating the Cognitive, Social, and Cultural Dimensions

Nancy J. Nersessian
Georgia Institute of Technology

Cognitive studies of science and technology ("cognitive studies") participate in two interdisciplinary fields: (a) cognitive science and (b) science and technology studies (STS). My analysis starts from issues about how cognitive studies are situated with respect to the social and cultural research programs in STS. As we will see, these issues have implications for how cognitive studies are situated within cognitive science as well. Within STS there is a perceived divide between cognitive accounts and social and cultural ("sociocultural"[1]) accounts of knowledge construction, evaluation, and transmission. Sociocultural accounts are dominant and have tended to claim that cognitive factors are inconsequential to interpreting these practices. Scientists are seen as having interests and motivations and as being members of cultures, but cognition remains, in effect, "black boxed." Cog-

[1]I categorize social and cultural accounts together here as *sociocultural* as a matter of convenience. "Social" and "cultural" are, of course, not coextensive notions, and analyses of these dimensions of scientific practice are quite diverse in the literature.

nitive studies accounts, for their part, have paid deference to the importance of the social and cultural dimensions of practice but have not, by and large, made these dimensions an integral part of their analyses. The situation has fostered a perception of incompatibility between cognitive and sociocultural accounts. One clear indication of this perception is the now-expired infamous "ten-year moratorium" on cognitive explanations issued first in 1986 by Bruno Latour and Stephen Woolgar (1986, p. 280; Latour, 1987, p. 247), by which time, they claimed, all pertinent aspects of science would be explained in terms of sociocultural factors. Perceptions to the contrary, any such divide is artificial. Producing scientific knowledge requires the kind of sophisticated cognition that only rich social, cultural, and material environments can enable. Thus, the major challenge for interpreting scientific and engineering knowledge-producing practices is to develop accounts that capture the fusion of the social–cognitive—cultural dimensions in these.

I argue in this chapter that the perception stems not from a fundamental incompatibility between cognitive and sociocultural accounts of science and technology but rather arises from the fact that integration has been hampered by implicit and explicit notions of "cognition" used on both sides of the perceived divide. Implicit echoes of Cartesian dualism underlie the anticognitive stance in sociocultural studies, leading to sociocultural reductionism. On this side, Cartesianism is rejected as untenable but, rather than developing an alternative theory to encompass cognitive explanatory factors, these are rejected outright. Within cognitive studies, these echoes are more explicit in their association with the traditional cognitive science view of cognition connected with GOFAI ("Good Old Fashioned AI" [coined by Haugeland, 1985]). The founding "functionalist" assumption of AI, that has in turn dominated cognitive science, is that thinking or intelligence is an abstractable structure that can be implemented in various media, including computers and humans. Cognitive reductionism identifies cognition with symbol processing that, in humans, takes place within an individual mind. Research in cognitive studies of science supports the position that important aspects of the representational and reasoning practices of scientists and engineers cannot be explained without invoking cognitive structures and processes. However, this large body of research, especially "*in vivo*" (coined by Dunbar, 1995) observational studies and "cognitive–historical" (coined by Nersessian, 1992; see also Nersessian, 1995b) studies, has led equally to recognizing that the social, cultural, and material environments in which science is practiced are critical to understanding scientific cognition (see, e.g., Dunbar 1995; Giere, 1988, 2002; Gooding, 1990; Gorman, 1997; Gorman & Carlson, 1990; Kurz & Tweney, 1998; Nersessian, 1984, 1995, 2002b; Thagard, 2000; Tweney, 1985, 2002). Accommodating these insights requires inserting a third approach to interpreting science and engineering practices—one that can serve as a *via media* in that it is nonreductive. The main purpose of this chapter, and an important part of the agenda for this volume, is to theorize cognition in relation to context or environment.

One route to attaining integration is to reconceptualize "cognition" by moving the boundaries of representation and processing beyond the individual so as to view scientific and engineering thinking as a complex system encompassing cognitive, social, cultural, and material aspects of practice. This direction is being pursued for accounts of mundane cognition in contemporary cognitive science, where proponents of such accounts refer to them as *embodied* and *embedded*. These accounts challenge central assumptions of GOFAI, and so the research is creating controversy within the field of cognitive science. To date, it has played little role in either cognitive or sociocultural studies of science. Accounts within this emergent research paradigm, which I call *environmental perspectives*, seek to provide explanations of cognition that give substantial roles to bodily and sociocultural factors. Advocates of environmental perspectives argue that the traditional symbol-processing view has mistaken the properties of a complex *cognitive system*, comprising both the individual and the environment, for the properties of an individual mind. They aim to develop an analytical framework in which cognitive processes are not separated from the contexts and activities in which cognition occurs. In this chapter I argue that a promising path to integration of cognitive and sociocultural dimensions of scientific and engineering practices lies in developing studies that both use the research of environmental perspectives on the social–cognitive–cultural nexus and contribute to its development.

THE CARTESIAN ROOTS OF COGNITIVE AND SOCIAL REDUCTIONISM IN STS

What, besides a penchant for rhetorical flourish, could explain such a pronouncement as the 10-year moratorium? One can agree that scientists are human in that they have interests, motivations, and sociocultural loci in conducting research. However, they also have sophisticated cognitive capabilities that historical records and contemporary practices provide strong evidence that they use in doing science. The roots of the position expressed in the 10-year moratorium pronouncement are complex in 20th-century intellectual history in that they arise as a reaction against a mix of issues, including the history of ideas approach to the history of science, the internal–external distinction in history and in sociology of science, the perceived hegemony of philosophical accounts of scientific knowledge, and the logicist "rules and representations" account of thinking of GOFAI analyses of science in early cognitive science. My concern here is with the Cartesian thread that runs through all of these.

The vision of early cognitive studies of science grew out of Herbert Simon's (Simon, Langley, & Bradshaw, 1981) important idea that scientific discovery involves problem-solving processes that are not different in kind from the problem-solving processes used in mundane circumstances. Coupled with the functionalist assumption of GOFAI, this insight led to attempts to abstract problem solving heuristics, and implement them in AI "scientific discovery" programs capable of making important scientific discoveries, such as was claimed for Kepler's laws (Langley, Simon, Bradshaw, & Zytkow, 1987) and the Krebs cycle (Kulkarni & Simon 1988). Those who dismiss cognitive explanations countered that when one studies, for example, the practices of high energy particle physicists, knowledge is produced not by what goes on in the mind of a solitary problem solver but by a "network" (Latour, 1987) or "mangle" (Pickering, 1995) of humans, machines, social arrangements, and cultures. Most researchers in contemporary cognitive studies would agree. Discovery programs are post hoc reconstructions. Once a solution is known, there are other ways to derive it. Once the data are known, a discovery program using good heuristics, such as BACON, can derive Kepler's laws. Later programs, such as KEKADA, used significant historical research (Holmes, 1980) to build systems that use many of the heuristics employed by Krebs, and, in this case, novel possible routes to the answer were also "discovered." However, what is missing from these computational accounts are the constructive processes of knowledge development, which are much more complex than simply using the appropriate heuristics. Why someone decides to collect such data, how data are selected as salient, what kinds of experimental devices and instruments are used and constructed for collection and analysis and how these are manipulated, how serendipity can play a role, and so forth, are all critical to constructing the knowledge that makes for a so-called "scientific discovery." However, discovery programs make up only a small fraction of the research in cognitive studies. The nonreductive nature of the social, cultural, and material environment is clear and agreed on in numerous cognitive studies accounts, such as those referenced earlier.

In my own research on Maxwell and the construction of the field concept, for example, I have repeatedly argued that even if one focuses on Maxwell's reasoning processes it matters a great deal to understanding how he derived the mathematical equations that Maxwell was trained in the Scottish geometrical (physical and visual) approach to using mathematics; was trained in Cambridge, England, as a mathematical physicist; was located in a milieu that valued Faraday's theoretical speculations as well as his experimental results, and included teachers and colleagues such as Thomson and his penchant for analogical models; and that he was

located in Victorian Britain where, among other factors, there was widespread cultural fascination with machines and mechanisms (Crosbie Smith & Wise, 1989; Davies, 2000; Nersessian, 1984, 1992, 2002b; Siegel, 1991). These sociocultural factors, taken together with cognitive factors, help to explain the nature of the theoretical, experimental, and mathematical knowledge and the methodological practices with which Maxwell formulated the problem and approached its solution. They are reflected in Maxwell's reasoning through mechanical models in deriving the equations, and one cannot understand his construction of these equations without taking these factors into account. Continental physicists working on electromagnetism at the time, such as Ampère, used quite different practices and drew from fundamentally different theoretical assumptions and mathematical and physical representational structures (see, e.g., Hoffman, 1996). Differences in sociocultural factors figure into why members of these communities were not able to derive the field equations. However, one also cannot explain the practices of either community without taking human cognition into account.

Why, then, are cognitive accounts that underscore the importance of sociocultural dimensions not seen as compatible with, or complementary to, sociocultural accounts? One likely issue is that many, though not all, of the cognitive analyses have individual scientists and inventors at their focus. These individuals, though, are conceived as engaging in a sociocultural activity. A Maxwell wrestling alone in his study with a problem is still engaged in a sociocultural process that includes the factors discussed earlier. To find the root of the conflict one needs to consider the issue of what notions of cognition inform the cognitive and the sociocultural sides of the debate.

Cognitive Reductionism

I will begin with the cognitive side, because these accounts make explicit use of cognitive science research. Cognitive studies accounts have been constructed largely without directly challenging the assumptions underlying the traditional cognitive science view of cognition, and this view contains vestiges of a Cartesian mind–body dualism. To connect this analysis with the discussion of environmental perspectives presented in the ENVIRONMENTAL PERSPECTIVES ON COGNITION section, it is useful to focus on the assumptions of the traditional view that are highlighted by these critics. On the traditional view, the cognitive system comprises the *representations* internal to an individual mind and the internal computational *processes* that operate on these. On the functionalist assumption of that view, thinking is "disembodied" in that it is independent of the medium in which it is implemented. Also, although the environment is represented in the content of thinking through being represented in memory, cognitive processing is independent of the social, cultural, and material environment, and thus cognition is not "embedded." Recently, these founding assumptions of cognitive science were reiterated and elaborated on by Alonso Vera and Herbert Simon (1993) in response to criticisms arising from within cognitive science.

In their article, Vera and Simon (1993) argued that the characterization of the traditional view by its critics, as outlined earlier, is a caricature, or at least rests on a misunderstanding of the original claims. They contended that the traditional view does not deny the importance of embodiment and sociocultural context to cognition—indeed, Simon's (1981, pp. 63–66) early "parable of the ant" recognizes that the complexity in the ant's behavior arises from acting in the environment. Rather, the claim is that what is important about the environment for thinking processes is abstracted through perception and represented in memory by the symbols generated by the cognitive system. The unit of analysis in studying cognition is a "physical symbol system" (see also Simon & Newell, 1972). A physical symbol system has a memory capable of storing and retaining symbols and symbol structures and a set of information processes that form structures as a function of sensory stimuli. In humans, and any natural or artificial physical symbol system with sensory receptors and motor action, sensory stimuli produce symbol structures that cause motor actions and modify symbol structures in memory. Thus, a physical symbol system can interact with the environment by (a) receiving sensory stimuli from it and converting these into symbol structures in memory and (b) acting upon it in ways determined by the symbol structures it produces, such as motor symbols. Perceptual and motor processes connect symbol systems with the environment and provide the semantics for the symbols. Clearly, then, Vera and Simon claimed, cognition is embodied and embedded but also takes place within the individual physical symbol system.

Granting the subtleties of Vera and Simon's (1993) rearticulation of the traditional view, one can see that it still complies with the Cartesian characterization. First, cognition is independent of the medium in which is it implemented. The physical nature of the patterns that constitute symbols is irrelevant. The processing algorithms are media independent. It makes no difference whether the medium is silicon or organic or anything else. So, 'mind' and 'medium' are independent categories. Second, the social and cultural environments in which cognition occurs are treated as abstract content on which cognitive processes operate. These dimensions are examined only as sociocultural knowledge residing inside the mind of a human individual or internal to other physical symbol systems.

Sociocultural Reductionism

Turning now to sociocultural studies, the conception of cognition that pervades this side of the perceived divide is largely implicit. It rests on folk notions that are uninformed by research in cognitive science, or even just in psychology. The best way to understand why these accounts reject the explanatory significance of factors pertaining to human cognition is to see the rejection as stemming from a tacit understanding of cognition that also retains vestiges of Cartesian dualism. The mind–body, individual–social, and internal–external dichotomies associated with Cartesianism are all in play on the sociocultural side as well, only this time they provide justification for rejecting cognitive explanatory factors—that is, rejecting these distinctions provides the grounds for rejecting cognitive explanations. As Latour (1999) argued, a cognitive explanation is tantamount to maintaining the epistemological position that the source of knowledge is ideas internal to the mind, where "mind" is a ghostly presence in a physical vessel. Cognitive explanations are cast out in a reactionary response to seeing dualism and GOFAI as providing the only possible ways of understanding 'mind' and 'cognition.' Reductionism is thus taken in the other direction. Sociocultural studies replace cognitive reductionism with sociocultural reductionism. Banishing cognitive explanatory factors amounts to "throwing out the baby with the bath water."

First, cognition is thrown out because it is identified with internal mental processes. Second, there is a disconnect between cognition and behavior. Actions are seen as resulting from the social, cultural, and material environments in which they occur, and from motivations and interests, which are customarily considered noncognitive factors. Cognition is "black boxed" and not part of the explanatory mix in analyzing knowledge construction. Third, the individual is held to be the wrong unit of analysis. In the "actor network," agency is not located specifically in humans. All actors—human and artifactual—are on equal footing. Cognition is rejected as an explanatory category because, traditionally, it belongs to individuals conceived as loci of solitary mental processing, independent of cultures and communities. These are all indications that an implicit belief that Cartesianism is "the only game in town" underlies sociocultural reductionism.

Rapprochement

Vestiges of Cartesianism on both sides of the divide in STS have been serving to create it. On the one hand, the traditional GOFAI account has not received explicit challenge from researchers in cognitive studies of science and engineering. On the other hand, a Cartesian conception of cognition serves as a basis for rejecting the relevance of cognitive explanatory factors by sociocultural studies. What is needed, instead, is a way of theorizing the cognitive, social, and cultural aspects of practice in relation to one another. Progress toward an integrative account is being hampered by assumptions from which research on both sides of the divide, in fact, points away. On the one side, the best way of reading the cumulative results of observational and cognitive–historical research in cognitive studies is as providing a challenge to the notion that the social, cultural, and material worlds of practice can be reduced to a few parameters in a traditional account of cognition. On the other side, the moratorium has ended. Indeed, even Latour (1999) has made good on his original promise (Latour 1987, p. 247) to "turn to the mind" if anything remained to be explained after the 10-year period. He has turned to the mind in order to discuss the relativism and realism debate in the "science wars," but what he says is pertinent here (Latour, 1999). Latour traced the roots of this debate to the Cartesian "mind-in-a-vat" that places the world external to mind and has that mind trying to understand the world by looking out from the vessel in which it resides (1999, pp. 4–10). He argued that research in sociocultural studies has established that knowledge production lies not within the mind but in the rich social, cultural, and material worlds of practices. Thus, the way forward is for mind to "*reconnect* through as many relations and vessels as possible with the rich vascularization that makes science flow" (1999, p. 113). Others in sociocultural studies are also moving toward accounts that can be read as taking note of cognition, such as Peter Galison's (1997) concern with the "image" and "logic" traditions in the material culture of particle physicists, Karin Knorr Cetina's (1999) recent analysis of scientific practices as part of "epistemic cultures," and Hans-Jörg Rheinberger's (1997) analysis of experimentation in molecular biology as producing "epistemic things." The time is ripe for rapprochement. Combined, research on the cognitive and sociocultural sides shows the divide to be artificial. There is a need for a new account of the social–cognitive–cultural nexus adequate to interpret scientific and engineering practices.

Within contemporary cognitive science there is movement toward an understanding of cognition, where "cognition refers not only to universal patterns of information transformation that transpire inside individuals but also to transformations, the forms and functions of which are shared among individuals, social institutions, and historically accumulated artifacts (tools and concepts)" (Resnick, Levine, & Teasley, 1991, p. 413). These accounts were not developed in response to the issues within STS discussed earlier, but I believe they offer significant groundwork for thinking about the integration problem. In the next section I present a brief analysis that weaves together significant threads of this research.

ENVIRONMENTAL PERSPECTIVES ON COGNITION

Some time ago, several cognitive scientists began expressing dismay with the "cognitive paradigm" as it had developed thus far and began calling for what they saw as a fundamental revisioning of the notion of cognition. Donald Norman (1981) posed the challenge:

> The human is a social animal, interacting with others, with the environment and with itself. The core disciplines of cognitive science have tended to ignore these aspects of behavior. The results have been considerable progress on some fronts, but sterility overall, for the organism we are analyzing is conceived as pure intellect, communicating with one another in logical dialog, perceiving, remembering, thinking when appropriate, reasoning its way through well-formed problems that are encountered in the day. Alas the description does not fit actual behavior. (p. 266)

Traditional cognitive science research attempts to isolate aspects of cognition to study it on the model of physics—the "spherical horses" approach.[2] Although traditional studies are still the mainstay of cognitive science, over the last 20 years significant investigations of cognition in authentic contexts of human activity such as learning and work have become numerous. These examinations range from studies of the effects of sociocultural milieu on categorization, conceptualization, and reasoning, to primate studies relating the emergence of culture and the evolution of human cognition, to neuroscience studies examining the potential of the human brain to be altered by the sociocultural environment of development. These various research thrusts can be characterized as attempts to account for the role of the environment (social, cultural, and material) in shaping and participating in cognition. Many of these analyses make *action* the focal point for understanding human cognition. Human actors are construed as thinking in complex environments; thus these analyses have emphasized that cognition is "embodied" (see, e.g., Barsalou, 1999; Glenberg, 1997; Glenberg & Langston, 1992; Johnson, 1987; Lakoff, 1987; Lakoff & Johnson, 1998) and "embedded," which, variously, are construed as "distributed" (see, e.g., Hutchins, 1995; Norman, 1988; Zhang, 1997; Zhang & Norman, 1995), "enculturated" (see, e.g., Donald, 1991; Nisbett, Peng, Choi, & Norenzayan, 2001; Shore, 1997; Tomasello, 1999), or "situated" (see, e.g., Clancey, 1997; Greeno, 1989a, 1998; Lave, 1988; Suchman, 1987).

[2]As noted by the editors of this volume, two significant metaphors pervaded the workshop on Cognitive Studies of Science and Technology. "Spherical horses" comes from a joke told by David Gooding: A multimillionaire offered a prize to whomever could predict the outcome of a horse race: a stockbreeder, a geneticist, or a physicist. The stockbreeder said there were too many variables, the geneticist said the prediction could not be made about any horse in particular, and the physicist claimed the prize: physics could make the prediction accurately to many decimal places, provided the horse were conceived as perfectly spherical and moving through a vacuum. "Shared toothbrushes" came from an observation made by Christian Schunn that, as with toothbrushes, no academic wants to use someone else's theoretical framework.

In contrast to the traditional cognitive science construal of the environment as mental content on which cognitive processes operate, these perspectives maintain that cognitive processes cannot be treated separately from the contexts and activities in which cognition occurs. For example, in arguing for a distributed notion of cognition, Edwin Hutchins (1995) contended that rather than construing culture as content and cognition as processing, what is required is for "cognition" and "culture" to be seen as interrelated notions construed in terms of *process*. Such construal leads to a shift in theoretical outlook from regarding cognitive and sociocultural *factors* as independent variables to regarding cognitive and sociocultural *processes* as integral to one another. The environmental perspectives maintain that the traditional view has mistaken the properties of a complex *cognitive system*, comprising individuals and environment, for the properties of an individual mind. The main points of contention are *not* whether the environment can be accommodated but rather *whether accounting for environmental factors requires altering fundamental notions of the structures and processes that make up cognition and of the methods through which to investigate cognition*. The argument is about the very nature of cognition and how to investigate it.

Broadly characterized, the challenges posed by the environmental perspectives to the traditional cognitive science view center on three interrelated questions: (a) What are the bounds of the cognitive system? (b) what is the nature of the processing used in cognition? and (c) what kinds of representations—internal and external—are used in cognitive processing? The literature of environmental perspectives is by now quite extensive, so it will not be possible to lay out any position in detail. Also, the research that falls under this label is wide ranging, and there is as yet not much dialogue among areas. What I present here is a way to read a cross-section of the literature so as to highlight features of research I see as most pertinent to the project of reconceptualizing the social–cognitive–cultural nexus in STS. I begin by discussing the "situative perspective" (Greeno, 1998) and then link aspects of other perspectives to this discussion.

Situated and Distributed Cognition

Much of the impetus for developing theories of *situated cognition* has come from studies conducted by cognitive anthropologists and sociologists concerned with learning and with work practices. Jean Lave, for instance, has attempted to explain ethnographical studies that establish striking disparities between mathematical problem-solving competency in the real world and in school learning environments. In real world environments, such as supermarkets (Lave, 1988) and Brazilian street markets (Carraher, Carraher, & Schliemann, 1983), adults and children exhibit high levels of competence in solving mathematics problems that are structurally of the

same kind as those they fail at solving in standard school and test formulations. Lave (1988) argued that the way to explain the disparities is to construe the relation between cognition and action as an interactive process in which the resources available in a specific environment play an essential role. Cognition is a relation between individuals and situations and does not just reside in the head. Explanations of human cognition in the situative perspective use the notion of *attunement to constraints and affordances*, adapted from Gibson's (1979) theory of perception. On the situative adaptation, an *affordance* is a resource in the environment that supports an activity, and a *constraint* is a regularity in a domain that is dependent on specific conditions.

The structure of an environment provides the constraints and affordances needed in problem solving, including other people, and these cannot be captured in abstract problem representations alone. In traditional cognitive science, problem solving is held to involve formulating in the abstract the plans and goals that will be applied in solving a problem. However, ethnographical studies of work environments by Lucy Suchman (1987) led her to argue that, contrary to the traditional cognitive science view, plans and goals develop in the context of actions and are thus *emergent* in the problem situation. Problem solving requires improvisation and appropriation of affordances and constraints in the environment, rather than mentally represented goals and plans specified in advance of action.

Within the situative perspective, analysis of a cognitive system, which James Greeno (1998) called an *intact activity system*, can focus at different levels: (a) on the individual, now conceptualized as an embodied, social, tool-using agent; (b) on a group of agents; (c) or on the material and conceptual artifacts of the context of an activity, or on any combination of these. In all cases, the goal is to understand cognition as an interaction among the participants in, and the context of, an activity. Cognition thus is understood to comprise the interactions between agents and environment, not simply the possible representations and processes in the head of an individual. In this way, situated cognition is *distributed*.

As with the situative perspective, the *distributed cognition* perspective contends that the environment provides a rich structure that supports problem solving. An environment does not, however, just supply scaffolding for mental processes, as the traditional view maintains. Rather, aspects of the environment are integral to the cognitive system and thus enter essentially into the analysis of cognition. To accommodate this insight, an account of cognitive processing needs to incorporate the *salient* resources in an environment in a nonreductive fashion. Salient resources are, broadly characterized, factors in the environment that can affect the outcome of an 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 the material from which the instrument is made usually would not. For physicists, sketching on a blackboard or whiteboard or piece of paper is likely irrelevant to solving a problem, but sketching on a computer screen might be salient, because the computer adds resources that can affect the outcome. On the other hand, sketching on a board usually takes place when others are present and possibly assisting in the problem solving, and sketching on paper is often done for oneself, and so other details of a case could change what is considered salient.

Determining the *cognitive artifacts* within a specific system is a major part of the analytical task for advocates of the distributed perspective. Hutchins (e.g., 1995) has studied the cognitive functions of artifacts used 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. Jiajie Zhang and Donald Norman (Zhang, 1997; Zhang & Norman, 1995), for example, have studied problem solving with isomorphic problems to ascertain potential cognitive functions of different kinds of visual representations. They found that external representations differentially facilitate and constrain reasoning processes. Specifically, they argue that diagrams can play more than just a supportive role in what is essentially an internal process; these external representations also can play a direct role in cognitive processing, without requiring the mediation of an internal representation of the information provided in them. The external representation can change the nature of the processing task, as when the tic-tac-toe grid is imposed on the mathematical problem of "15." One way this research contributes to breaking down the external–internal distinction is by expanding the notion of memory to encompass external representations and cues; that is, specific kinds of affordances and constraints in the environment are construed, literally, as memory in cognitive processing. Thus, Zhang and Norman (1995) argue that analysis of cognition in situations of problem solving with diagrams needs to be at the level of the cognitive system that comprises both the mental and diagrammatic representations.

Research in the situative and distributed perspectives largely consists of observational case studies in which ethnographic methods are used. Although these studies focus on details of particular cases and often provide "thick descriptions" of these (Geertz, 1973), their objective differs from sociocultural studies in STS that aim mainly to ferret out the specific details of a case. The aim of the cognitive science research discussed here is to understand the nature of the regularities of cognition in human activity. Hutchins framed that objective succinctly:

> There are powerful regularities to be described at the level of analysis that transcends the details of the specific domain. It is not possible to discover these regularities without understanding the details of the domain, but the regularities are not about the domain specific details, they are about the nature of cognition in human activity. (Hutchins, as quoted in Woods, 1997, p. 117)

Currently there are many research undertakings that share the situated cognition and distributed cognition objective of furthering an account that construes cognition and environment in relation to one another. Research in all environmental perspectives areas is very much research in progress, so it tends to focus internally to an area, without much interaction across them. In the remainder of this section I provide a brief tour through significant research programs that, when considered as comprising a body of interconnected research, offer a substantially new way of understanding human cognition and of thinking about the social–cognitive–cultural nexus in science and engineering practices.

Embodied Mental Representation

Individual human agents are parts of cognitive systems, and an accounting of the nature of their mental representations and processes is an outstanding research problem for environmental perspectives. Some research in distributed cognition makes use of mainstream notions of mental representation, such as mental models and concepts. The most radical proponents of the situative perspective, however, go so far as to contend that mental representations play no role in cognitive processes. Driving a car around a familiar campus provides an example of an activity that might not require use of a mental map of the campus; the affordances and constraints in the environment could suffice for navigating to one's office. However, it is difficult to see how complex problem-solving practices, such as those in science and engineering, could simply make use of environmental affordances and constraints. A more moderate position, such as the one articulated by Greeno (1989b), maintains that although not all cognitive practices need to use mental representations, and not all information in a system needs to be represented mentally, some kinds of practices might use them. Scientific and engineering problem-solving practices are prime candidates for practices that use mental representations. However, it is unlikely that environmental perspectives can simply adopt traditional cognitive science understandings of these representations.

In thinking about the human component of a cognitive system, a line of research that examines the implications of the *embodied* nature of human cognition potentially can be appropriated. Embodied cognition focuses on the implications of the interaction of the human perceptual system with the environment for mental representation and processing. Proponents contend that there is empirical evidence that perceptual content is retained in mental representations and that perceptual and motor processes play a significant role in cognitive processing (see, e.g., Barsalou, 1999; Craig, Nersessian, & Catrambone, 2002; Glenberg, 1997; Johnson, 1987; Kosslyn, 1994; Lakoff, 1987). Psychologist Lawrence Barsalou (1999) formulated a theory of "perceptual symbol systems" that calls into question the traditional understanding of mental representation as *amodal*, or composed of symbols that are arbitrary transductions from perception. He argued, rather, that there is an extensive experimental literature that can be read as supporting the contention that mental representations retain perceptual features, or are *modal*. On Barsalou's account, cognitive processing uses "perceptual symbols," which are neural correlates of sensory experiences. These representations possess *simulation* capabilities; that is, perceptual and motor processes associated with the original experiences are re-enacted when perceptual symbols are used in thinking. One implication of this account is that situational information should be retained in concept representations, and there is abundant evidence from psychological experiments supporting this (Yeh & Barsalou, 1996). Thus, affordances and constraints of situational information can be at play even in using conceptual understanding in activities, such as in problem solving.

One highly influential account of the embodied nature of mental representation has been provided by George Lakoff and Mark Johnson, who argue that mental representations arise through metaphorical extension from bodily experiences. All representations, no matter how abstract, they contend, can be shown to derive from fundamental kinesthetic *image schemas* that structure experience prior to the formation of conceptual representations. An example of an image schema that pervades human thinking is the "*container*" schema with "*in*" and "*out*" as primary reference points to the human body (Lakoff, 1987, p. 252). The notion of being trapped in a marriage and getting out of it reflects this image schema. Another is the more complex "*force*" schema, with *interaction*, *directionality*, *path*, *origin*, and *degree* as dimensions of fundamental bodily interactions in the world (Johnson, 1987, pp. 41–42). One uses this schema when, for example, talking of having writer's block. Conceptual structures are cast as developing out of such schemas and thus as being meaningful in terms of these. Lakoff and Johnson argue that metaphorical extension is a universal cognitive mechanism that can accommodate observed individual and cultural variability in conceptual structure.

Cognition and Culture

In *Culture in Mind*, anthropologist Bradd Shore (1997) addressed the problem of the role of universal cognitive mechanisms in the development of mental representations, the content of which are culturally variable and context relative. His approach to the problem draws on ethnographic studies of various cultural groups to examine the interplay between the "cultural affordances" offered by local sociocultural structures and the universal cognitive processes involved in meaning making in the creation of "cultural models" exhibited in local practices. Cultural models have two dimensions: (a) the publicly available, or "instituted" form, such as in rituals and games, and (b) the mental construct or "mental model" that individuals create and use to understand the world. The instituted forms are not simply "faxed" to the mind but "undergo a variety of transformations as they are brought to mind" (Shore, 1997, p. 52). Shore's account of the transformative processes of constructing mental models uses the notion of meaning construction as involving processes of metaphorical extension, developed by Lakoff and Johnson. Shore concluded that although there are possibly an infinite variety of cultural models, the relations between culture and cognition are governed by such universal cognitive mechanisms.

Comparative studies between humans and other primates in primatology research and in the area of cognitive development have led Michael Tomasello (1999; Tomasello & Call, 1997), among others, to contend that cognition is inherently cultural. He argues that culture is central to the development of uniquely human cognitive abilities, both phylogenetically and ontogenetically. The question of the origins of these unique abilities is a key problem for understanding cognitive development. From the perspective of biological evolution, the time span is just too short to account for the vast cognitive differences that separate humans from the primates closest to them genetically, the chimpanzees. On the basis of experimental and observational studies of ontogenesis in human children and in other primates, Tomasello posits that the development of the uniquely human cognitive abilities began with a small phylogenetic change in the course of biological evolution: the ability to see conspecifics as like oneself and thus to understand the intentionality of one's actions. This change has had major consequences in that it enabled processes of imitation and innovation that allow for the accumulation of culture through transmission—what Tomasello (1999) calls *cultural evolution*.

According to the account Tomasello (1999) developed, cultural evolution is the engine of cognitive evolution; that is, he claims that the expansion of cognitive capacities in the human primate has occurred as an adaptation to culture. It is significant, then, that this account theorizes culture not as something added to accounts of cognition—culture is what makes human cognition what it is. Human cognition and culture have been co-evolving. The cultural tools of each generation (including language development) are left behind for the next generation to build upon. Tomasello (1999) called this the "rachet effect." Regardless of the fate of his claim about the root of this ability lying in a *uniquely* human ability to understand conspecifics as intentional beings (recent work shows that other primates, and dogs, might also possess the ability; Agnetta, Hare, & Tomasello, 2000; Tomasello, Call, & Hare, 1998), humans are unique in the way they pass on and build on culture. In ontogenesis, children absorb the culture and make use of its affordances and constraints in developing perspectively based cognitive representations. Tomasello (1999) argued that language development plays a crucial role in creating cognitive capacities in the processes of ontogenesis. This view parallels the early speculations of Lev Vygotsky (1978), whose work has influenced the development of the situative perspective discussed earlier. Vygotsky argued that cognitive development is sociocultural in that it involves the internalization of external linguistic processes.

Another influential comparative account that examines the relations between culture and the development of human cognitive capacities is offered by the evolutionary psychologist Merlin Donald (1991), who uses a wide range of evidence from anthropology, archaeology, primatology, and neuroscience to argue his case. One aspect of this account reinforces the notion that not all cognitive processing need be of internal representations. External representations are indispensable in complex human thinking, and their development has been 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 (40,000 years ago), writing (6,000 years ago) and phonetic alphabets (4,000 years ago). He 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 account, affordances and constraints in the environment are, *ab initio*, part of cognitive processing.

Research into the relations between culture and cognition, together with neuroscience research into cognitive development, can be construed as moving beyond the old nature–nurture debate and developing an *interactionist* approach. It attempts to provide an account of how evolutionary endowment and sociocultural context act together to shape human cognitive development. In support of this conception, neuroscience studies of the impact of sociocultural deprivation, enrichment, and trauma on brain structure and processes lead to a conception of the brain as possessing significant cortical plasticity and as a structure whose development takes place in response to the sociocultural environment as well as to genetic inheritance and biological evolution (see, e.g., Elman et al., 1998; van der Kolk, McFarlane, & Weisaeth, 1996).

Finally, in so connecting cognition and culture, this body of research indicates that human cognition should display both universal and culturally specific characteristics. Tomasello (1999, pp. 161–163) discussed some of the universal learning abilities, such as those connected with language learning; these include the ability to understand communicative intentions, to use role reversal to reproduce linguistic symbols and constructions, and to use linguistic symbols for contrasting and sharing perspectives in discourse interactions. Recent investigations by Richard Nisbett and his colleagues (Nisbett et al., 2001) provide evidence of culturally specific features of cognition. Their research examined learning, reasoning, problem solving, representation, and decision making for such features. This research was also inspired by the substantial body of historical scholarship that maintains that there were systematic cultural differences between ancient Greek and Chinese societies, especially concerning what Nisbett et al. (2001) call the "sense of personal *agency*" (p. 292). Nisbett et al. hypothesized that these kinds of differences between so-called Eastern and Western cultures, broadly characterized as holistic versus analytic thinking (p. 293), should be detectable in a wide range of cognitive processes, such as categorization, memory, covariation detection, and problem solving.

The comparative contemporary cultures in Nisbett et al.'s (2001) study are those whose development has been influenced either by ancient China (China, Japan, and Korea) or by ancient Greece (western Europe and North America). In a series of experiments with participants from east Asian and Western cultures, and participants whose families had changed cultural location, Nisbett et al. examined explanations, problem solving, and argument evaluation. Some significant systematic differences were found along the five dimensions they identified in the ancient cultures (in the order Eastern vs. Western): (a) focusing on continuity versus on discreteness, (b) focusing on field versus on object, (c) using relations and similarities versus using categories and rules, (d) using dialectics in reasoning versus using logical inference from assumptions and first principles, and (e) using experienced-based knowledge in explanations versus using abstract analysis. Although Nisbett et al.'s grouping of very diverse cultures into such gross categories as "Eastern" and "Western" is problematic, the general results are intriguing and promise to lead to further research into the issue of culturally specific features of cognition.

Environmental Perspectives and the Integration Problem

Situating the problem of interpreting scientific and engineering practices with respect to the framework provided by environmental perspectives on cognition affords the possibility of analyzing the practices from the outset as bearing the imprint of human cognitive development, the imprint of the sociocultural histories of the localities in which science is practiced, and the imprint of the wider societies in which science and technology develop. The implications of the growing body of environmental-perspectives research for the project of constructing integrative accounts of knowledge-producing practices in science and engineering are extensive. Working them out in detail is beyond the scope of any one chapter. One approach to exploring the implications would be to recast some of the analyses in the literatures of both cognitive studies and sociocultural studies of science and engineering in light of it. Here, for example, I am thinking of such research as by Cetina, Galison, Giere, Gooding, Gorman, Latour, Rheinberger, Tweney, and myself, cited earlier.

Another approach would be to undertake new research projects that aim from the outset at integration. In the next section I offer my current research project on interpreting knowledge-producing practices in biomedical engineering research laboratories as an exemplar of an integrative approach. This project combines ethnographic studies with cognitive–historical analyses to examine reasoning and representational practices. My colleagues and I are examining these research practices at all of the levels of analysis noted by Greeno (1998) for situated cognitive systems: at the level of researchers as individual, embodied, social, tool-using agents; at the level of groups of researchers; at the level of the material and conceptual artifacts of the context of laboratory activities; and at various combinations of these.

RESEARCH LABORATORIES AS EVOLVING DISTRIBUTED COGNITIVE SYSTEMS

Science and engineering research laboratories are prime locations for studying the social–cognitive–cultural nexus in knowledge-producing practices. Extensive STS research has established that laboratory practices are located in rich social, cultural, and material environments. However, these practices make use of sophisticated cognition in addressing research problems. In this section I discuss some features of my current research project that has among its aims the interpretation of reasoning and representational practices used in problem solving in biomedical engineering (BME) laboratories. The research both appropriates and contributes to research within the environmental perspectives discussed in the previous section. My colleagues and I do not adopt or apply any particular theory but rather use a cross-section of that thinking about the nature of cognition as a means of framing our investigation into these research practices. We are influenced also by research on both sides of the supposed divide in STS. As a contribution to STS, specifically, we aim to develop analyses of the creation

of BME knowledge in which the cognitive and the sociocultural dimensions are integrated analytically from the outset. Our focus is on the cognitive practices, but we analyze cognition in BME laboratories as situated in localized reasoning and representational practices. This is collaborative research that would not be possible without an interdisciplinary team.[3] The case study has been underway for less than 2 years, so the analysis presented here is preliminary. Nevertheless, it provides a useful exemplar of how integration might be achieved.

We have begun working in multiple sites, but here I discuss a specific tissue engineering laboratory, Laboratory A, that has as its ultimate objective the eventual development of artificial blood vessels. The daily research is directed toward solving problems that are smaller pieces of that grand objective. Our aim is to develop an understanding of (a) the nature of reasoning and problem solving in the laboratory; (b) the kinds of representations, tools, forms of discourse, and activities used in creating and using knowledge; (c) how these support the ongoing research practices; and (d) the nature of the challenges faced by new researchers as they are apprenticed to the work of the laboratory.

We conceive of and examine the problem-solving activities in Laboratory A as *situated* and *distributed*. These activities are situated in that they lie in localized interactions among humans and among humans and technological artifacts. They are distributed in that they take place across systems of humans and artifacts. BME is an *interdiscipline* in that melding of knowledge and practices from more than one discipline occurs continually, and significantly new ways of thinking and working are emerging. Most important for our purposes is that innovation in technology and laboratory practices happens frequently, and learning, development, and change in researchers are constant features of the laboratory environment. Thus, we characterize the laboratory as comprising "evolving distributed cognitive systems." The characterization of the cognitive systems as *evolving* adds a novel dimension to the existing literature on distributed cognition, which by and large has not examined these kinds of creative activities.

Investigating and interpreting the cognitive systems in the laboratory has required innovation, too, on the part of our group of researchers studying the laboratory. To date, ethnography has been the primary method for investigating situated cognitive practices in distributed systems. As a method

[3]This research is conducted with Wendy Newstetter (co-PI), Elke Kurz-Milcke, Jim Davies, Etienne Pelaprat, and Kareen Malone. Within this group of cognitive scientists we have expertise in ethnography, philosophy of science, history of science, psychology, and computer science. We thank our research subjects for allowing us into their work environment and granting us numerous interviews, and we gratefully acknowledge the support of the National Science Foundation Research on Learning and Education Grant REC0106773.

it does not, however, suffice to capture the critical *historical* dimension of the research laboratory: the evolution of technology, researchers, and problem situations over time that are central in interpreting the practices. To capture the evolving dimension of the laboratory, we have developed a mixed-method approach that includes both ethnography and cognitive–historical analysis.

A Mixed-Method Approach to Investigating Evolving Distributed Cognitive Systems

None of the conceptions of distributed cognition in the current literature account for systems that have an evolving nature. In Hutchins's (1995) studies of distributed cognition in work environments—for instance, the cockpit of an airplane or on board a ship—the problem-solving situations change in time. The problems faced, for example, by the pilot change as she is in the process of landing the plane or bringing a ship into the harbor. However, the nature of the technology and the knowledge that the pilot and crew bring to bear in those processes are, by and large, stable. Even though the technological artifacts have a history within the field of navigation, such as the ones Hutchins documented for the instruments aboard a ship, these do not change in the day-to-day problem-solving processes on board. Thus, these kinds of cognitive systems are dynamic but largely *synchronic*. In contrast, we are studying cognition in innovative, creative settings, where artifacts and understandings are undergoing change over time. The cognitive systems of the BME research laboratory are, thus, dynamic and *diachronic*. Although there are loci of stability, during problem-solving processes the components of the systems undergo development and change over time. The technology and the researchers have evolving, *relational* trajectories that must be factored into understanding the cognitive system at any point in time. To capture the evolving dimension of the case study we have been conducting both cognitive–historical analyses of the problems, technology, models, and humans involved in the research and ethnographic analyses of the day-to-day practices in the laboratory.

Ethnographic analysis seeks to uncover the situated activities, tools, and interpretive frameworks used in an environment that support the work and the ongoing meaning-making of a community. Ethnography of science and engineering practices aims to describe and interpret the relations between observed practices and the social, cultural, and material contexts in which they occur. Our ethnographic study of the BME laboratory develops traces of transient and stable arrangements of the components of the cognitive systems, such as evidenced in laboratory routines, the organization of the workspace, the artifacts in use, and the social organization of the laboratory at a particular point in time, as they unfold in the daily research activities and

ground those activities. Ethnographic studies of situated sociocultural practices of science and engineering are abundant in STS (see, e.g., Bucciarelli, 1994; Latour & Woolgar, 1986; Lynch, 1985). However, studies that focus on situated *cognitive* practices are few in number in either STS or in cognitive science. Furthermore, existing observational (Dunbar, 1995) and ethnographic studies (see, e.g., Goodwin, 1995; Hall, Stevens, & Torralba, in press; Ochs & Jacoby, 1997) of scientific cognition lack attention to the historical dimension that we find important to our case study.

Cognitive–historical analysis enables one to follow trajectories of the human and technological components of a cognitive system on multiple levels, including their physical shaping and reshaping in response to problems, their changing contributions to the models that are developed in the laboratory and the wider community, and the nature of the concepts that are at play in the research activity at any particular time.[4] As with other cognitive–historical analyses, we use the customary range of historical records to recover how the representational, methodological, and reasoning practices have been developed and used by the BME researchers. The practices can be examined over time spans of varying length, ranging from shorter spans defined by the activity itself to spans of decades or more. The aim of cognitive–historical analysis is to interpret and explain the generativity of these practices in light of salient cognitive science investigations and results (Nersessian, 1992, 1995b). Saliency is determined by the nature of the practices under scrutiny. In this context, the objective of cognitive–historical analysis is not to construct an historical narrative; rather, the objective is to enrich understanding of cognition in context by examining how knowledge-producing practices originate, develop, and are used in science and engineering domains.

In STS there is an extensive literature in the cognitive studies area that uses cognitive–historical analysis. My own studies and those of many others have tended to focus on historical individuals, including Faraday, Maxwell, and Bell, and on developing explanatory accounts of concept formation, concept use, and conceptual change (Andersen, 1996; Chen, 1995; Gooding, 1990; Gorman, 1997; Gorman & Carlson, 1990; Nersessian, 1985, 1992, 2002b; Tweney, 1985). Many of these studies have argued for the significance of the material context of concept formation, with special focus on a wide range of external representations in interpreting concept formation practices, such as Gooding's (1990) study of how Faraday's concept of "electromagnetic rotations" emerged through complex interactions with sketches on paper and prototype apparatus, my own on the generative

[4]For a comparison of cognitive–historical analysis to other methodologies—laboratory experiments, observational studies, and computational modeling—used in research on scientific discovery, see Klahr and Simon (1999).

role of the lines-of-force diagram on the development of his field concept (Nersessian, 1984, 1985), and Tweney's recent work on various physical manipulations of microscope slides in Faraday's developing understanding of gold (Tweney, 2002; chap. 7, this volume). They have also shown the importance of sociocultural context, as, for example, in Gooding's (1989) account of the origins of Faraday's lines-of-force concept in the material and communicative strategies of other practitioners and in my (Nersessian, 1984, 1992, 2002b) discussions of the context of Maxwell's modeling practices in mathematizing the electromagnetic field concept as noted in the section titled THE CARTESIAN ROOTS OF COGNITIVE AND SOCIAL REDUCTIONISM IN STS. When studying contemporary science and engineering, what ethnography adds is the possibility of examining both the social, cultural, and material contexts of as they currently exist and the practices as they are enacted.

In our study of BME practices thus far, the analyses are focused on the technological artifacts that push BME research activity and are shaped and reshaped by that activity. Ethnographic observations and interviews have indicated the saliency of specific artifacts in the social–cognitive–cultural systems of the laboratory, as I discuss in the section titled "THE BME LABORATORY AS AN EVOLVING DISTRIBUTED COGNITIVE SYSTEM." These artifacts become and remain part of the laboratory's history. The cognitive–historical analyses focus on reconstructing aspects of the laboratory's history. How the members of the laboratory appropriate the history and use and alter the artifacts in their daily research in turn become the focus of our ethnographic analyses. We aim to construct an account of the *lived relation* that develops between the researchers and specific artifacts, rather than an account of the developing knowledge about these artifacts *per se*. By focusing on the lived relations we mean to emphasize the activity of the artifacts in a relational account of distributed cognitive systems. These lived relations have cognitive, social, and cultural dimensions. Combining cognitive–historical analysis with ethnography allows examination of these relationships *in situ*, as they have developed—and continue to develop—in time. It is important that developing a relationship with an artifact entails appropriating its history, which chronicles the development of the problem situation, including what is known about the artifact in question. The researchers, for instance, include postdoctoral fellows, PhD students, and undergraduates, all of whom have learning trajectories. These trajectories, in turn, intersect with the developmental trajectories of the diverse technological artifacts and of the various social systems within the laboratory.

Users of an artifact often redesign it in response to problems encountered, either of a technical nature or to bring it more in accord with the *in vivo* model. To begin research, a new participant must first master the relevant aspects of the existing history of an artifact necessary to the research and then figure out ways to alter it to carry out her project as the new research problems demand, thereby adding to its history. For example, one highly significant technological artifact in Laboratory A is the *flow loop*, an engineered device that emulates the shear stresses experienced by cells within blood vessels (see Fig. 2.1). A PhD student we interviewed discussed how the previous researcher had modified the block to solve some technical problems associated with bacterial contamination—a constant problem in this line of research. The flow loop, as inherited by the new student, had previously been used on smooth muscle cells. The new student was planning to use the flow loop to experiment with vascular constructs of endothelial cells that are thicker than the muscle cells and not flat. Because the vascular constructs are not flat, spacers need to be used between the block and the glass slides in order to improve the flow pattern around the boundary to bring the *in vitro* model more in accord with the *in vivo* model. To begin that research she, together with another new student, had to re-engineer the flow loop by changing the width of the flow slit to hold the spacers.

Making sense of the day-to-day cognitive practices in a BME laboratory and constructing cognitive histories of artifacts are prima facie separate tasks. However, that the research processes in the distributed cognitive systems of Laboratory A evolve at such a fast pace necessitates going back and forth between the two endeavors. The ethnographic observations of the development, understanding, and use of particular artifacts by various laboratory members, as well as ethnographic interviews, have enabled us to conjoin the cognitive–historical study of laboratory members, laboratory objects, and the laboratory itself with an eye on the perception of these entities by the laboratory members themselves.

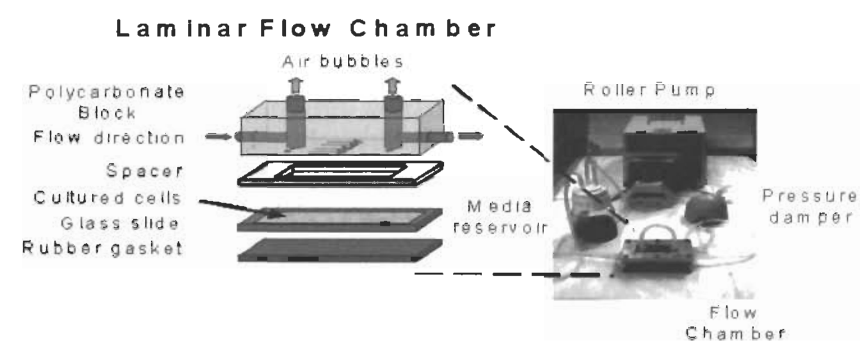

FIG. 2.1. Diagram and photograph of a flow loop.

The BME Laboratory as an Evolving Distributed Cognitive System

Laboratory A applies engineering principles and methods to study living cells and tissues with the goal of eventual development of artificial blood vessels to implant in the human cardiovascular system. The laboratory members come from predominantly engineering backgrounds. They tend to seek biological knowledge on an as-needed basis. Biological knowledge is embedded in the artifacts the researchers construct for simulation purposes and other model-based reasoning they use in the course of research. Early experimentation in this area was conducted by the principal investigator (PI) and others with animals *in vivo* and *ex vivo* (substitutes implanted but not kept within the body). However, *in vivo* research has many limitations, such as that one cannot test the strength of various kinds of scaffolding for blood vessels. The research has now moved *in vitro*, through the design of facsimiles of relevant aspects of the *in vivo* environment. These technological facsimiles are locally constructed sites of *in vitro* experimentation.

A major research goal is to optimize *in vitro* models so as to move closer and closer to *in vivo* situations. When used within the human body, the bioengineered substitutes must replicate the functions of the tissue being replaced. This means that the materials used to "grow" these substitutes must coalesce in a way that mimics the properties of native tissues. It also means that the cells embedded in the scaffolding material must replicate the capabilities of native cells so that the higher level tissue functions can be achieved. Moreover, the cells must be readily available. This requires developing methods and technologies for ensuring cell growth, proliferation, and production.

In vitro research in Laboratory A starts with culturing blood vessel cells, smooth muscle cells, and endothelial cells. Cells are embedded in various scaffolding materials and stimulated in environments that mimic certain aspects of the current understanding of flow processes in an effort to improve them—for example, making them proliferate or making them stronger. A significant part of creating artificial blood vessels is to have them withstand the mechanical forces associated with blood flow through vessels *in vivo*. Much of the technology created by the laboratory serves this purpose. Cells are stimulated in the *in vitro* simulation environments, and various instruments are used to extract and process information, most often pertaining to stress and strain, such as measures of elasticity (linear modulus), shear stress, ultimate tensile stress, toughness (the amount of energy it takes to break a construct), and cell volume and health under mechanical stimulation.

There are many dimensions along which to develop the analysis of the laboratory as an evolving distributed cognitive system and of the systems within it. In the following sections, I focus on our recasting of some traditional cognitive science interpretive notions by which we are attempting to break down the internal–external distinction—a major impediment to integrating cognitive and sociocultural dimensions of scientific and engineering practices. In these analyses it is important to keep in mind that (a) our use of the notion of "distributed cognitive system" to understand the problem-solving practices within the BME laboratory is for analytical purposes and is not intended to reify the systems and (b) what a system encompasses both in space and in time—that is, its "boundaries"—is, in our analysis, relative to a problem-solving process.

The Laboratory as "Problem Space." The laboratory, as we construe it, is not simply a physical space existing in the present but rather a *problem space*, constrained by the research program of the laboratory director, that is reconfiguring itself almost continually as the research program moves along and takes new directions in response to what occurs both in the laboratory and in the wider community of which the research is a part. At any point in time the laboratory-as-problem-space contains resources for problem solving that comprise people, technology, techniques, knowledge resources (e.g., articles, books, artifacts, the Internet), problems, and relationships. Construed in this way, the notion of "problem space" takes on an expanded meaning from that customarily used in the traditional cognitive science characterization of problem solving as a search through an *internally* represented problem space. Here the problem space comprises both. Researchers and artifacts move back and forth between the wider community and the physical space of the laboratory. Thus the problem space has permeable boundaries.

For instance, among the most notable and recent artifacts (initiated in 1996) in Laboratory A are the tubular-shaped, bioengineered cell-seeded vascular grafts, locally called *constructs* (see Fig. 2.2). These are physical models of native blood vessels engineered to eventually function as viable implants for the human vascular system. The endothelial cells the laboratory uses in seeding constructs are obtained by researchers traveling to a distant medical school and bringing them into the problem space of the laboratory. On occasion, the constructs or substrates of constructs travel with laboratory members to places outside of the laboratory. Recently, for example, one of the graduate students has been taking substrates of constructs to a laboratory at a nearby medical school that has the elaborate instrumentation to perform certain kinds of genetic analysis (microarrays). This line of research is dependent on resources that are currently available only outside Laboratory A in the literal, spatial sense. The information produced in this locale is brought into the problem space of the laboratory by the researcher and figures in the further problem-solving activities of the laboratory.

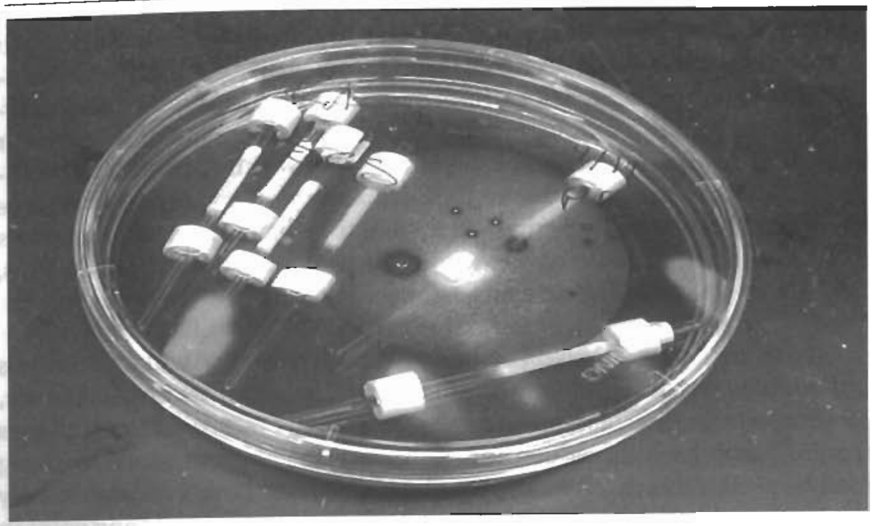

FIG. 2.2. Photograph of a Dish of Vascular Constructs.

Following Hutchins (1995), my colleagues and I analyze the cognitive processes implicated in a problem-solving episode as residing in a *cognitive system* comprising both one or more researchers and the *cognitive artifacts* involved in the episode (see also Norman, 1991). In line with his analysis, a *cognitive system* is understood to be sociotechnical in nature, and *cognitive artifacts* are material media possessing the cognitive properties of generating, manipulating, or propagating representations.[5] So, right from the outset, the systems within the laboratory are analyzed as social–cognitive–cultural in nature. Determining the cognitive artifacts within any cognitive system involves issues of agency and intention that are pressing questions for cognitive science research, both in the development of the theoretical foundations of distributed cognition and in relation to a specific case study. On our analysis, not all parts of the cognitive system are equal. Only the researchers have agency and intentions, which enable the cognitive activities of specific artifacts.

Our approach to better understanding such issues is to focus on the technology used in experimentation. During a research meeting with the laboratory members, including the PI, we asked them to sort the material artifacts in the laboratory according to categories of their own devising and rank the importance of the various pieces to their research. Their classification in terms of "devices," "instruments," and "equipment" is represented in Table

[5]For related notions in the STS literature, see also Rheinberger (1997) on "epistemic things" and Tweney (2002) on "epistemic artifacts."

2.1. Much to the surprise of the PI, the newer PhD students initially wanted to rank some of the equipment, such as the pipette, as the most important for their research, whereas for the PI and the more senior researchers deemed the devices the laboratory engineers for simulation purposes as most important to the research. Additional ethnographic observations have led us to formulate working definitions of the categories used by Laboratory A's researchers. *Devices* are engineered facsimiles that serve as *in vitro* models and sites of simulation;[6] *instruments* generate measured output in visual, quantitative, or graphical form; and *equipment* assists with manual or mental labor.

Distributed Model-Based Reasoning. As noted earlier, an *in vivo–in vitro* division is a significant component of the cognitive framework guiding practice in Laboratory A. Because the test bed environment for developing artificial blood vessels cannot be the human body in which they will ultimately be implanted, the BME researchers have to design facsimiles of the *in vivo* environment where the experiments can be conducted. These devices pro-

TABLE 2.1
Sorting of Laboratory Artifacts by the Laboratory Members

Ontology of Artifacts		
Devices	*Instruments*	*Equipment*
Flow loop	Confocal	Pipette
Bioreactor	Flow cytometer	Flask
Equi-biaxial strain	Mechanical tester	Water bath
Construct	Coulter counter	Refrigerator
	"Beauty and beast"	Sterile hood
	LM 5 (program)	Camera
	computer	

[6]We are using the term "device" because this is how the researchers in the laboratory categorized the *in vitro* simulation technology. This notion differs from the notion of "inscription devices" that Latour and Woolgar (1986, p. 51) introduced and that has been discussed widely in the STS literature. The latter are devices for literally creating figures or diagrams of phenomena. The former are sites of *in vitro* simulation, and further processing with instruments is necessary to transform the information provided by these devices into visual representations or quantitative measures.

vide locally constructed sites of experimentation where *in vitro* models are used to screen and control specific aspects of the *in vivo* phenomena they want to examine. Devices, such as the construct, the flow loop, and the bioreactor (discussed later), are constructed and modified in the course of research with respect to problems encountered and changes in understanding. Studying the devices underscores how the kinds of systems we are investigating diverge from those investigated by Hutchins (1995). The devices are not stable technological artifacts but have a history within the research of the laboratory. For example, the flow loop was first created in the research of the PI of this laboratory to simulate "known fluid mechanically imposed wall sheer stress"—in other words, to perform as a model of hemodynamics.[7] We have traced aspects of its development since 1985. The constructs were first devised in Laboratory A in 1996 as an important step in the overall objective of creating vascular substitutes for implantation. They afford experimentation not only on cells but also on structures more closely related to the *in vivo* model. The bioreactor, although having a longer and more varied history outside the laboratory, first made its appearance in this laboratory in conjunction with the tubular constructs and was not used anywhere before for that purpose. The current smooth muscle constructs are not strong enough to withstand the mechanical forces in the human (or animal) cardiovascular system. The *bioreactor* is used to stimulate the cells mechanically with the objective of changing their mechanical properties. The *equi-biaxial strain*, which simulates blood vessel expansion and contraction, is the newest device created specifically for this laboratory and is just starting to be used.

The cognitive artifacts in the distributed systems in the laboratory cut across the categories, although most are devices or instruments. Analysis of the ethnographic data has focused our attention on the devices, all of which we classify as cognitive artifacts. Devices instantiate models of the cardiovascular system and serve as *in vitro* sites of experimentation with cells and constructs under conditions simulating those found in the vascular systems of organisms. It is in relation to the researcher's intent of performing a simulation with the device to create new situations that parallel potential real world situations, and the activity of the device in so doing, that qualifies a device as a cognitive artifact within the system. For example, as a device, the flow loop *represents* blood flow in the artery. In the process of simulation, it *manipulates* constructs that are *representations* of blood vessel walls. After

[7]Although some of the material we quote from comes from published sources, given the regulations governing confidentiality for human subjects research, if the authors are among subjects we are not able to provide citations to that material here. It seems that the possibility of conducting historical research in conjunction with human subjects research was not anticipated! Laboratory A researchers are given an alias, "A plus a number," e.g., A10.

being *manipulated*, the constructs are then removed and examined with the aid of instruments, such as the confocal microscope, which *generates* images for many color channels, at multiple locations, magnifications, and gains. These *manipulations* enable the researchers to determine specific things, such as the number of endothelial cells and whether the filaments align with the direction of flow, or to simply explore the output, just "looking for stuff." Thus, the *representations generated* by the flow loop *manipulations* of the constructs are *propagated* within the cognitive system.

Devices perform as models instantiating current understanding of properties and behaviors of biological systems. For example, the flow loop is constructed so that the behavior of the fluid is such as to create the kinds of mechanical stresses experienced in the vascular system. However, devices are also systems themselves, possessing engineering constraints that often require simplification and idealization in instantiating the biological system they are modeling. For example, the flow loop is "a first-order approximation of a blood vessel environment ... as the blood flows over the lumen, the endothelial cells experience a shear stress ... we try to emulate that environment. But we also try to eliminate as many extraneous variables as possible" (laboratory researcher A10). So, as with all models, devices are idealizations.

The bioreactor provides an example of how the devices used in the laboratory need to be understood both as models of the cardiovascular system and as a systems in themselves. The bioreactor is used for many purposes in the field but, as used in Laboratory A, it was re-engineered for "mimicking the wall motions of the natural artery" (see Fig. 2.3). It is used to expose the constructs to mechanical loads in order to improve their overall mechanical properties. The researchers call this process *mechanical conditioning*—or, as one researcher put it, "exercising the cells." This preferably is done at an early stage of the formation of the construct, shortly after seeding the cells onto a prepared tubular silicon sleeve. *In vivo*, arterial wall motion is conditioned on pulsatile blood flow. With the bioreactor, though, which consists of a rectangular reservoir containing a fluid medium (blood-mimicking fluid) in which the tubular constructs are immersed and connected to inlet and outlet ports off the walls of the reservoir, "fluid doesn't actually move," as one laboratory member put it, "which is somewhat different from the actual, uh, you know, real life situation that flows." The sleeves are inflated with pressurized culture medium, under pneumatic control (produced by an air pump). The medium functions as an incompressible fluid, similar to blood. By pressurizing the medium within the sleeves, the diameter of the silicon sleeve is changed, producing strain on the cells, similar to that experienced *in vivo*. The bioreactor is thus a functional model of pulsatile blood flow, and needs to be understood by the researcher as such.

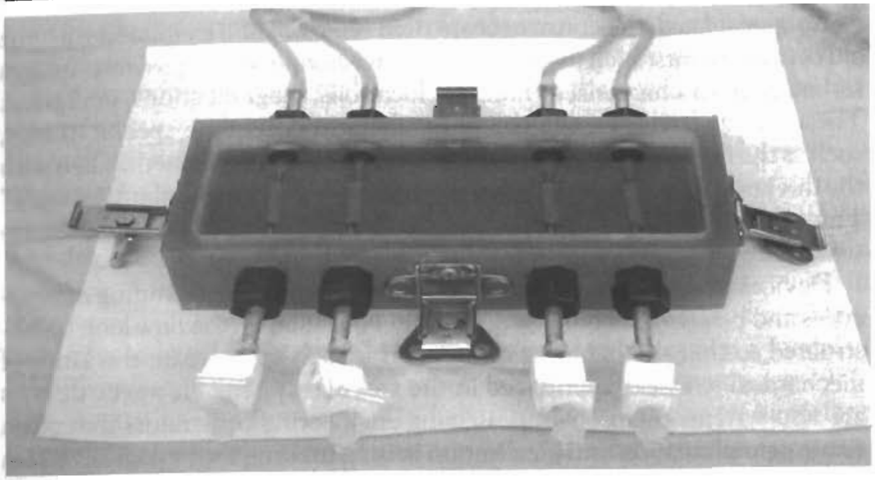

FIG. 2.3. Photograph of a Bioreactor.

Distributed Mental Modeling. Significant to our reconceiving the internal–external distinction is that the problem space comprises mental models and physical artifacts together with a repertoire of activities in which simulative model-based reasoning assumes a central place. Many instances of model-based reasoning in science and engineering use external representations that are constructed during the reasoning process, such as diagrams, sketches, and physical models. In line with the discussion of such representations in the ENVIRONMENTAL PERSPECTIVES ON COGNITION section, these can be seen to provide constraints and affordances essential to problem solving that augment those available in whatever internal representations are used by the reasoner during the process. In this way, "cognitive capabilities" are understood to encompass more than "natural" capabilities. The devices used in Laboratory A are physical models used in the problem solving. Within the cognitive systems in the laboratory, then, devices instantiate part of the current community model of the phenomena and allow simulation and manipulation. The intent of the simulation is to create new situations *in vitro* that parallel potential *in vivo* situations.

One researcher we interviewed called the processes of constructing and manipulating these *in vitro* sites "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. The "bench top," as one researcher explained, is not the flat table surface but comprises all the locales where experimentation takes place. In previous research, I (Nersessian, 1999, 2002a) have characterized the reasoning involved in

simulative model-based reasoning as a form of dynamic mental modeling, possibly using iconic representations. There the focus was on thought experiments, and that analysis used the notion of a mental model in the traditional manner as referring to an internal object of thought. In the current research, I am expanding the notion of simulating a mental model to comprise both what are customarily held to be the internal thought processes of the human agent and the processing of the external device. Simulative model-based reasoning involves a process of coconstructing the "internal" researcher models of the phenomena and of the device and the "external" model that is the device, each incomplete. Understood in this way, simulating the mental model would consist of processing information both in memory and in the environment; that is, the mental modeling process is distributed in the cognitive system.[8]

Cognitive Partnerships. Our account of the distributed cognitive systems in the laboratory characterizes cognition in terms of the lived relationships among the components of these systems, people, and artifacts. In Laboratory A these relationships develop in significant ways for the individual laboratory members and for the community as a whole. Newcomers to the laboratory, who are seeking to find their place in the evolving system, initially encounter the cognitive artifacts as materially circumscribed objects. For example, one new undergraduate who was about to use the *mechanical tester*, an instrument for testing the strength of the constructs (see Fig. 2.4), responded to our query about the technology she was going to use in her research project:

> A2: I know that we are pulling little slices of the construct—they are round, we are just pulling them. It's the machine that is right before the computer in the lab. The one that has the big "DO NOT TOUCH" on it.
>
> I: Is it the axial strain (mechanical tester)?
>
> A2: I know it has a hook on it and pulls.

The novice researcher can describe the mechanical tester at this point in time as nothing more than parts. Another example is provided by the sorting task recounted in the section titled "The Laboratory as 'Problem Space,' " where novice researchers saw the equipment as more important to

[8]Of course, I use the term "mental" provocatively here, as a rhetorical move to connect the discussion with aspects of the traditional notion of mental modeling and extend the notion for use in the distributed-cognition framework. For related attempts to reconceive mental modeling, see Greeno (1989b) on the relation between mental and physical models in learning physics and Gorman (1997) on the relation between mental models and mechanical representations in technological innovation.

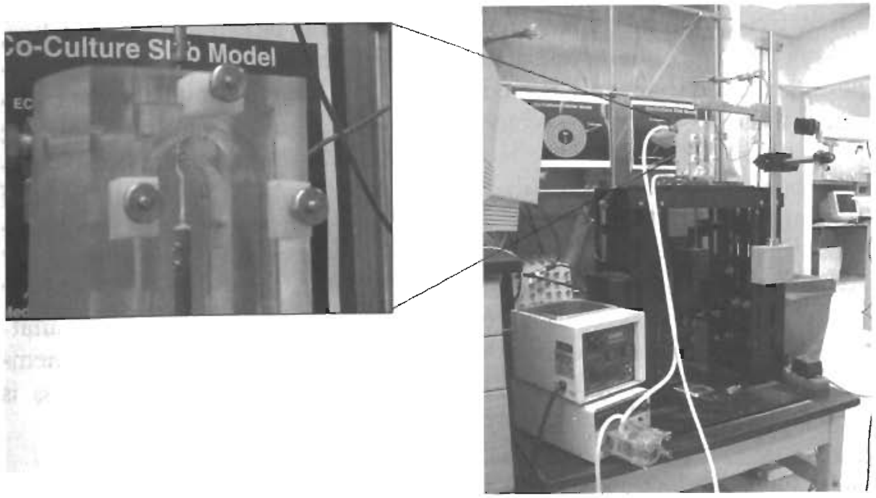

FIG. 2.4. Photograph of the mechanical tester with close-up of hook mechanism.

their research than the simulation devices. We propose that growing cognitive membership in the laboratory involves a gradual process of coming to understand these objects as devices—as objects with evolving trajectories, constructed and used to respond to problems, to help answer questions, and to generate new ones. Thus, we find that one cannot divorce research from learning in the context of the laboratory and that learning involves building relationships with people and with artifacts.

We characterize the relationships between the various technological artifacts in the cognitive system and the researchers as *cognitive partnerships*. These partnerships provide the means for generating, manipulating, and propagating representations within the distributed cognitive systems of this research laboratory. Over time, understandings are constructed, revised, enhanced, and transformed through partnerships between the researchers and the artifacts in the community. As relationships change, so too do knowledge and participation.

The cognitive partnerships transform both researcher and artifact. A researcher who some months earlier was a newcomer and who saw the artifacts as just many kinds of machines and objects piled on shelves and on the bench top now can see a device as an *in vitro* site for "putting a thought [his/her thought] into the bench top and seeing whether it works or not." During the problem-solving processes involved in instantiating a thought and seeing if it works, devices are re-engineered, as exemplified above with the flow loop. Re-engineering is possible because the researcher with a developed partnership appropriates and participates in the history of a device. A senior PhD researcher, at that point in time, considered the "resident expert" on the bioreactor, was able easily to reconstruct some of his lived relationship with it and some of its history within this laboratory:

> I: Do you sometimes go back and make modifications? Does that mean you have some generations of this?
>
> ... Uh yes I do. The first generation and the second generation or an offshoot I guess of the first generation. Well the first one I made was to do mechanical loading and perfusion. And then we realized that perfusion was a much more intricate problem than we had—or interesting thing to look at—than we had guessed. And so we decided okay we will make a bioreactor that just does perfusion on a smaller scale, doesn't take up much space, can be used more easily, can have a larger number of replicates, and so I came up with this idea.

He continued by pulling down previous versions of bioreactor (made by earlier researchers as well) and explaining the modifications and problems for which design changes were made. His account suggests a developed partnership.

Furthermore, in developed partnerships potential device transformations can be envisioned, as with one undergraduate research scholar we interviewed about the bioreactor:

> A16: I wish we could accomplish—would be to actually suture the actual construct in there somehow. To find a way not to use the silicon sleeve.... That would really be neat. Um, simply because the silicon sleeves add the next level of doubt. They're—they are a variable thing that we use, they're not always 100% consistent. Um the construct itself is not actually seeing the pressure that the sleeve does. And because of that you know, it doesn't actually see a—a pressure. It feels the distension but it doesn't really feel the pressure. It doesn't have to withstand the pressure. That's the whole idea of the sleeve. And so, um, I think that it would provide a little bit more realism to it. And uh, because that also, a surgeon would actually want to suture the construct into a patient. And um, because of that you're also mimicking the patient as well—if you actually have the construct in the path. I think another thing is to actually have the flow because um, so this flow wouldn't be important with just the sleeve in there. But if you had the construct in contact with the—with the liquid that's on the inside, you could actually start to flow media through there.

In this case an undergraduate student has been transformed over the course of several semesters to a BME researcher, contributing to immediate research goals; who transforms artifacts in his immediate research; who understands the outstanding problems and objectives; and who can envision how a device might change from a functional model to a model more closely paralleling the *in vivo* situation to push the research along. At this point in evolution, thinking is taking place through the cognitive partnering of the researcher and device. In their established form, relationships with artifacts entail cognitive partnerships that live in *interlocking* models performing internally as well as externally.

Implications of the Exemplar for Integration

Our approach to interpreting the knowledge-producing practices in the laboratory contributes to the project of developing means of interpreting cognitive, social, and cultural dimensions of practice in relation to one another. By starting from the perspective that cognition is embedded in complex environments, the laboratory's innovative problem-solving practices are interpreted as social–cognitive–cultural from the outset. The mixed methodology enables both thick descriptions of specific systems and hypotheses about "the nature of cognition in human activity" that go beyond the specifics of the laboratory under study. Consider the outline of our analysis of the flow loop. It is a major cognitive tool developed and used in the model-based reasoning in this laboratory. It is a significant cultural artifact, originating in the research program of the PI and then passed down through generations[9] of researchers, enabling each to build on the research of others, while sometimes being re-engineered as an artifact in the service of model-based reasoning. It is a locus for social interaction, such as that involved in learning and didactical interaction between mentor and apprentice. At one point it served as the vehicle for initiation into the community of practice, although at present cell culturing serves this purpose, because the problem situation has evolved, and now the flow loop is no longer the only experimental device. On the one hand, the histories of the lived relations among the flow loop and researchers can be developed into thick social–cognitive–cultural descriptions of the evolving systems of the laboratory. On the other hand, understanding the role of the flow loop as a device—a cognitive artifact for performing simulative model-based reasoning in the problem-solving activities within the distributed cognitive systems of the laboratory—leads to hypotheses about the nature of reasoning and representation. The mixed methodology facilitates the capture and analysis of the dynamics of the interplay among the cognitive, social, and cultural dimensions of scientific and engineering practices.

[9]Approximately 5 years marks a generational shift in this research, although different generations of researchers are in the laboratory at any one time.

CONCLUSIONS

The reductionism of the physical symbol system notion does not do justice to the practices of science and engineering, such as the complex relationship with the material environment, the highly distributed nature of reasoning in laboratory environments and elsewhere, and the extensive use of external representations in reasoning and communicating. These aspects of practice need to be factored into an account of cognition as more than simply content over which internal cognitive processes operate and as doing more than just providing scaffolding for cognition. The environmental perspectives on cognition provide a framework within which to do this. At the same time, studying reflexively the cognitive practices of scientists and engineers contributes to the task of developing that account of cognition.

STS accounts that see cognition as inconsequential in creating knowledge also do not do justice to these practices. Moreover, even if we start from the perspective that cognition is distributed within a system, there is always at least one human in the knowledge-making system, and often an individual plays a pivotal role: Maxwell's equations were formulated by Maxwell (in original form, of course). So the contribution of the individual human component in the system needs also to be understood: Internal representations and processes are still important. However, they need to be understood as inherently integrated with the "external" environment. Again, environmental perspectives, viewed in the interrelated way of the ENVIRONMENTAL PERSPECTIVES ON COGNITION section, assist in developing a framework in which to do this. The analysis presented in the RESEARCH LABORATORIES AS EVOLVING DISTRIBUTED COGNITIVE SYSTEMS section is my current way of approaching integration.

Integrating the cognitive and the sociocultural will have major implications for STS. Likewise, implications from studying cognition with respect to scientific and engineering practices stand to have a major impact on cognitive science. Take the following as one example. The physical symbol system notion assumes that cognitive processes are universal and the same through recorded history, so there is thought to be no need to contextualize or historicize theories of problem solving, learning, and decision making. In this cognitive science has modeled itself on physics—the phenomena to be explained are the "spherical horses." From the perspective of sociocultural analyses, scientific knowledge-producing practices have changed with changes in cultural assumptions, including values, and with developments in such things as instrumentation and mathematical representational systems. These changes are traditionally accommodated as changes in *what* scientists think about—that is, the content of representations changes culturally and historically—and not as changes in *how* scientists think, that is, in the nature of cognitive representations and processing. But if we reconceptualize "cognition," moving the boundaries beyond the individual to complex systems encompassing salient aspects of the environments of practice—that is, conceptualize cognition as distributed and situated in the environment and as lying in the interactions among parts of the system—what are the implications of these historical sociocultural changes for understanding scientific cognition—or, for that matter, ordinary cognition?

At this stage in the project of integration we are left with many unresolved issues. What is sure is that interpreting scientific and engineering practices requires s shift from looking at cognitive factors and sociocultural factors as independent variables in explanations of these practices to regarding cognitive processes as inherently sociocultural, and vice versa. Doing this requires rethinking foundational and methodological issues in cognitive science and in STS together—with the goal of creating "shared toothbrushes"—and we are only at the beginning of this process.

ACKNOWLEDGMENTS

I thank Elke Kurz-Milcke, Thomas Nickles, and the editors of this volume for their comments on earlier versions of this chapter. I appreciate also the comments made on an earlier version of this chapter by the participants in the "Cognitive Studies of Science" workshop organized by the Danish Graduate Research School in Philosophy, History of Ideas, and History of Science, especially Hanne Andersen, Ronald Giere, and Thomas Söderqvist. Finally, I gratefully acknowledge the support of the National Science Foundation in carrying out this research: Science and Technology Studies Scholar's Award SBE9810913 and Research on Learning and Education Grant REC0106773.

I dedicate this chapter to the memory of Frederic Lawrence Holmes, friend, mentor, and inspiration.

REFERENCES

Agnetta, B., Hare, B., & Tomasello, M. (2000). Cues to food location that domestic dogs (*Canis familiaris*) of different ages do and do not use. *Animal Cognition, 3*, 107–112.

Andersen, H. (1996). Categorization, anomalies, and the discovery of nuclear fission. *Studies in the History and Philosophy of Modern Physics, 27*, 463–492.

Barsalou, L. W. (1999). Perceptual symbol systems. *Behavioral and Brain Sciences, 22*, 577–609.

Bucciarelli, L. L. (1994). *Designing engineers*. Cambridge, MA: MIT Press.

Carraher, T. D., Carraher, D. W., & Schliemann, A. D. (1983). Mathematics in the streets and schools. *British Journal of Developmental Psychology, 3*, 21–29.

Cetina, K. K. (1999). *Epistemic cultures: How the sciences make knowledge*. Cambridge, MA: Harvard University Press.

Chen, X. (1995). Taxonomic changes and the particle-wave debate in early nineteenth-century Britain. *Studies in the History and Philosophy of Science, 26*, 251–271.

Clancey, W. J. (1997). *Situated cognition: On human knowledge and computer representations*. Cambridge, England: Cambridge University Press.

Craig, D. L., Nersessian, N. J., & Catrambone, R. (2002). Perceptual simulation in analogical problem solving. In L. Magnani & N. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 169–187). New York: Kluwer Academic/Plenum.

Davies, G. E. (2000). *The democratic intellect*. Edinburgh, Scotland: Edinburgh Press.

Donald, M. (1991). *Origins of the modern mind: Three stages in the evolution of culture and cognition*. Cambridge, MA: Harvard University Press.

Dunbar, K. (1995). How scientists really reason: Scientific reasoning in real-world laboratories. In R. J. Sternberg & J. E. Davidson (Eds.), *The nature of insight* (pp. 363–395). Cambridge, MA: MIT Press.

Elman, J. L., Bates, E. A., Johnson, M., Karmiloff-Smith, A., Parisi, D., &. Plunkett, K. (1998). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: MIT Press.

Galison, P. (1997). *Image and logic: A material culture of microphysics*. Chicago: University of Chicago Press.

Geertz, C. (1973). *The interpretation of cultures*. New York: Basic Books.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Giere, R. N. (1988). *Explaining science: A cognitive approach*. Chicago: University of Chicago Press.

Giere, R. N. (2002). Scientific cognition as distributed cognition. In P. Carruthers, S. Stich, & M. Siegal (Eds.), *The cognitive basis of science* (pp. 285–299). Cambridge, England: Cambridge University Press.

Glenberg, A. M. (1997). What memory is for. *Behavioral and Brain Sciences, 20*, 1–55.

Glenberg, A. M., & Langston, W. E. (1992). Comprehension of illustrated text: Pictures help to build mental models. *Journal of Memory and Language, 31*, 129–151.

Gooding, D. (1989). "Magnetic curves" and the magnetic field: Experimentation and representation in the history of a theory. In D. Gooding, T. Pinch, & S. Schaffer (Eds.), *The uses of experiment* (pp. 183–244). Cambridge, England: Cambridge University Press.

Gooding, D. (1990). *Experiment and the making of meaning: Human agency in scientific observation and experiment*. Dordrecht, The Netherlands: Kluwer.

Goodwin, C. (1995). Seeing in depth. *Social Studies of Science, 25*, 237–274.

Gorman, M. (1997). Mind in the world: Cognition and practice in the invention of the telephone. *Social Studies of Science, 27*, 583–624.

Gorman, M. E., & Carlson, W. B. (1990). Interpreting invention as a cognitive progress: The case of Alexander Graham Bell, Thomas Edison, and the telephone. *Science, Technology, and Human Values, 15*, 131–164.

Greeno, J. G. (1989). A perspective on thinking. *American Psychologist, 44*, 134–141.

Greene, J. G. (1989b). Situations, mental models, and generative knowledge. In D. Klahr & K. Kotovsky (Eds.), *Complex information processing* (pp. 285–318). Hillsdale, NJ: Lawrence Erlbaum Associates.

Greene, J. G. (1998). The situativity of knowing, learning, and research. *American Psychologist, 53*, 5–24.

Hall, R., Stevens, R., & Torralba, T. (2002). Disrupting representational infrastructure in conversation across disciplines. *Mind, Culture, and Activity*, 9, 179–210.

Haugeland, J. (1985). *Artificial intelligence: The very idea*. Cambridge, MA: MIT Press.

Hoffman, J. R. (1996). *Andre-Marie Ampere*. Cambridge, England: Cambridge University Press.

Holmes, F. L. (1980). Hans Krebs and the discovery of the ornithine cycle. *Federation Proceedings, 39,* 216–225.

Hutchins, E. (1995). *Cognition in the wild.* Cambridge, MA: MIT Press.

Johnson, M. (1987). *The body in the mind: The bodily basis of meaning, imagination, and reason.* Chicago: University of Chicago Press.

Klahr, D., & Simon, H. A. (1999). Studies of scientific discovery: Complimentary approaches and divergent findings. *Psychological Bulletin, 125,* 524–543.

Kosslyn, S. M. (1994). *Image and brain.* Cambridge, MA: MIT Press.

Kulkarni, D., & Simon, H. A. (1988). The processes of scientific discovery: The strategy of experimentation. *Cognitive Science, 12,* 139–175.

Kurz, E. M., & Tweney, R. D. (1998). The practice of mathematics and science: From calculus to the clothesline problem. In M. Oaksford & N. Chater (Eds.), *Rational models of cognition* (pp. 415–438). Oxford, England: Oxford University Press.

Lakoff, G. (1987). *Women, fire, and dangerous things: What categories reveal about the mind.* Chicago: University of Chicago Press.

Lakoff, G., & Johnson, M. (1998). *Philosophy in the flesh.* New York: Basic Books.

Langley, P., Simon, H. A., Bradshaw, G. L., & Zytkow, J. M. (1987). *Scientific discovery: Computational explorations of the creative processes.* Cambridge, MA: MIT Press.

Latour, B. (1987). *Science in action.* Cambridge, MA: Harvard University Press.

Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies.* Cambridge, MA: Harvard University Press.

Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts.* Princeton, NJ: Princeton University Press.

Lave, J. (1988). *Cognition in practice: Mind, mathematics, and culture in everyday life.* New York: Cambridge University Press.

Lynch, M. (1985). *Art and artifact in laboratory science: A study of shop work and shop talk in a research laboratory.* London: Routledge and Kegan Paul.

Nersessian, N. J. (1984). *Faraday to Einstein: Constructing meaning in scientific theories.* Dordrecht, The Netherlands: Martinus Nijhoff/Kluwer Academic.

Nersessian, N. (1985). Faraday's field concept. In D. C. Gooding & F. A. J. L. James (Eds.), *Faraday rediscovered: Essays on the life & work of Michael Faraday* (pp. 337–406). London: Macmillan.

Nersessian, N. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. Giere (Ed.), *Minnesota studies in the philosophy of science* (pp. 3–45). Minneapolis: University of Minnesota Press.

Nersessian, N. (1995). Opening the black box: Cognitive science and the history of science. *Osiris, 10,* 194–211.

Nersessian, N. (1999). Model-based reasoning in conceptual change. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 5–22). New York: Kluwer Academic/Plenum.

Nersessian, N. (2002a). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal (Eds.), *The cognitive basis of science* (pp. 133–153). Cambridge, England: Cambridge University Press.

Nersessian, N. (2002b). Maxwell and the "method of physical analogy": Model-based reasoning, generic abstraction, and conceptual change. In D. Malament (Ed.), *Reading natural philosophy: Essays in the history and philosophy of science and mathematics* (pp. 129–163). Lasalle, IL: Open Court.

Nisbett, R., Peng, K., Choi, I., & Norenzayan, A. (2001). Culture and systems of thought: Holistic v. analytic cognition. *Psychological Review, 108,* 291–310.

Norman, D. A. (1981). *Perspectives on cognitive science.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Norman, D. A. (1988). *The psychology of everyday things.* New York: Basic Books.

Norman, D. A. (1991). Cognitive artifacts. In J. M. Carroll (Ed.), *Designing interaction* (pp. 17–38). Cambridge, England: Cambridge University Press.

Ochs, E., & Jacoby, S. (1997). Down to the wire: The cultural clock of physicists and the discourse of consensus. *Language in Society, 26,* 479–505.

Pickering, A. (1995). *The mangle of practice: Time, agency, and science.* Chicago: University of Chicago Press.

Resnick, L. B., Levine, J., & Teasley, S. (Eds.). (1991). *Perspectives on socially shared cognition.* Washington, DC: American Psychological Association.

Rheinberger, H.-J. (1997). *Toward a history of epistemic things: Synthesizing proteins in the test tube.* Stanford, CA: Stanford University Press.

Shore, B. (1997). *Culture in mind: Cognition, culture and the problem of meaning.* New York: Oxford University Press.

Siegel, D. (1991). *Innovation in Maxwell's electromagnetic theory.* Cambridge, England: Cambridge University Press.

Simon, H. A. (1981). *The sciences of the artificial* (2nd ed.). Cambridge, MA: MIT Press.

Simon, H. A., Langley, P. W., & Bradshaw, G. L. (1981). Scientific discovery as problem solving. *Synthese, 47,* 1–27.

Simon, H. A., & Newell, A. (1972). *Human problem solving.* Englewood Cliffs, NJ: Prentice Hall.

Smith, C., & Wise, M. N. (1989). *Energy and empire: A biographical study of Lord Kelvin.* Cambridge, England: Cambridge University Press.

Suchman, L. A. (1987). *Plans and situated actions: The problem of human–machine communication.* Cambridge, England: Cambridge University Press.

Thagard, P. (2000). *How scientists explain disease.* Princeton, NJ: Princeton University Press.

Tomasello, M. (1999). *The cultural origins of human cognition.* Cambridge, MA: Harvard University Press.

Tomasello, M., & Call, J. (1997). *Primate cognition.* Oxford, England: Oxford University Press.

Tomasello, M., Call, J., & Hare, B. (1998). Five primates follow the visual gaze of conspecifics. *Animal Behavior, 55,* 1063–1069.

Tweney, R. D. (1985). Faraday's discovery of induction: A cognitive approach. In D. Gooding & F. A. J. L. James (Eds.), *Faraday rediscovered* (pp. 189–210). New York: Stockton.

Tweney, R. D. (2002). Epistemic artifacts: Michael Faraday's search for the optical effects of gold. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 287–304). New York: Kluwer Academic/Plenum.

van der Kolk, B., McFarlane, A. C., & Weisaeth, L. (Eds.). (1996). *Traumatic stress: The effects of overwhelming experience on mind, body, and society.* New York: Guildford.

Vera, A., & Simon, H. (1993). Situated cognition: A symbolic interpretation. *Cognitive Science, 17,* 4–48.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.

Woods, D. D. (1997). Towards a theoretical base for representation design in the computer medium: Ecological perception and aiding human cognition. In J. Flack, P. Hancock, J. Cairn, & K. Vincente (Eds.), *The ecology of human–machine systems* (pp. 157–188). Hillsdale, NJ: Lawrence Erlbaum Associates.

Yeh, W., & Barsalou, L. W. (1996). The role of situations in concept learning. *Proceedings of the 18th annual conference of the Cognitive Science Society* (pp. 460–474). Mahwah, NJ: Lawrence Erlbaum Associates.
Zhang, J. (1997). The nature of external representations in problem solving. *Cognitive Science, 21*, 179–217.
Zhang, J., & Norman, D. A. (1995). A representational analysis of numeration systems. *Cognition, 57*, 271–295.

3

Causal Thinking in Science: How Scientists and Students Interpret the Unexpected

Kevin N. Dunbar
Jonathan A. Fugelsang
Dartmouth College

Scientists have attempted to delineate the key components of scientific thinking and scientific methods for at least 400 years (e.g., Bacon, 1620/1854; Galilei, 1638/1991; Klahr, 2000; Tweney, Doherty, & Mynatt, 1981). Understanding the nature of the scientific mind has been an important and central issue not only for an understanding of science but also what it is to be human. Given the enduring and wide-ranging interest in the scientific mind, there has been a multiplicity of ways used to investigate the genesis of scientific concepts, theories, and hypotheses. Most important to bear in mind is that many of the methods that have been used to understand science have been tied to changes in their respective fields of study. In philosophy, for example, the switch from an analytical to a more historically based approach resulted in major shifts in an understanding of science (Callebaut, 1992). Likewise, in psychological studies of scientific thinking there has been continuous discourse between advocates of naturalistic studies of human behavior and advocates of highly controlled experiments (Dunbar, 2000; Dunbar & Blanchette, 2001; Tweney et al., 1981). In fact, naturalistic versus highly constrained or controlled investigations has been a central