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Peripheral Vision

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Abstract

A central challenge for science studies researchers in developing accounts of knowledge construction in science and engineering is to integrate the cognitive, social, cultural, and material dimensions of practice. Within science studies there is a perceived divide between cognitive practices, on the one hand, and cultural practices, on the other. Any such divide, though at times analytically useful, is artificial. Producing scientific knowledge requires the kind of sophisticated cognition that only rich social, cultural, and material environments can enable. This paper aims to move in the direction of an integrative account of these dimensions of practice. It discusses model-based reasoning practices in biomedical engineering research laboratories construed as 'evolving cognitive-cultural systems'.

Keywords: cognition, model-based reasoning, knowledge construction, practice, cognitive-cultural system

Introduction: The Problem of Interpretive Integration

Accounts of science and engineering research practices tend to line up on either side of a perceived divide between cultural[1] factors and cognitive factors in knowledge construction, evaluation, and transmission. Cultural accounts largely 'black-box' cognitive factors, since they are viewed as being inconsequential to explaining how science works. Cognitive accounts, while paying deference to the importance of the cultural dimensions of practice, have, with few exceptions, not made cultural factors an integral part of the analysis. The situation has fostered a perception of incompatibility between cognitive and cultural accounts of science and engineering practices. Perceptions to the contrary, in the conduct of research any such divide is artificial. Inquiry in science and engineering requires the kind of sophisticated cognition that only rich cultural environments can enable. In considering, for instance, the problem-solving activities of a research laboratory, both factors contribute to formulating research problems and pursuing their solutions. Thus, the major challenge for analyzing such practices is to develop accounts that capture the integrated nature of the cultural and cognitive factors in the problem-solving situations.

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With the objective of analytical integration the trick is to create accounts that are neither primarily cognitive with culture tacked on, nor the reverse, and this requires critical thinking about current interpretive categories. One way of capturing the relations among cognition and culture in practice is to theorize cognition in relation to context, as has recent cognitive science research on mundane cognition. 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. What I dub '*environmental perspectives'* emphasize that cognition is *embodied* (see, e.g., Barsalou 1999; Glenberg and Langston 1992; Glenberg 1997; Johnson 1987; Lakoff 1987; Lakoff and Johnson 1998), *distributed* (see, e.g., Hutchins 1995; Norman 1988; Zhang and Norman 1995; Zhang 1997), *enculturated* (see, e.g., Donald 1991; Nisbett et al. 2001; Shore 1997; Tomasello 1999) and *situated* (see, e.g., Clancey 1997; Greeno 1989a, 1998; Lave 1988; Suchman 1987).

Environmental perspectives argue that the traditional internal symbol-processing view of cognitive science has mistakenly attributed to the individual mind what are the properties of a complex, *cognitive system*, comprising both the individual and the environment. In contrast to the standard 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, Hutchins (1995) contends 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 analytical approach from regarding cognitive and cultural factors as independent variables to regarding cognitive and cultural processes as integral to one another. One route to attaining analytical integration with science and engineering practices is to follow a path similar to the environmental perspectives and move the boundaries of representation and processing for cognition beyond the individual so as to view scientific and engineering problem-solving as occurring in complex *cognitive-cultural* systems.

Research Laboratories as Evolving Cognitive-Cultural Systems

Science and engineering research laboratories are prime locations for studying the cognitive-cultural nexus in knowledge-producing practices. Extensive ethnographic and historical research has established that laboratory practices are located in rich social, cultural, and material environments. So too, however, these practices address research problems through using sophisticated cognition. Much less research addresses the nature of cognitive practices, and the major work by Kevin Dunbar (Dunbar 1995) on research laboratories in molecular biology analyzes cognition in a more traditional manner as internal symbol-processing. This paper will discuss some features of my current research project that has as among its aims understanding problem-solving practices in interdisciplinary biomedical engineering (BME) laboratories. The research both appropriates and contributes to research within the environmental perspectives mentioned in the previous section. In conducting this research, we do not adopt or apply any particular theory among these perspectives, but rather draw from a cross-section of that research as a means of framing our investigation into BME research practices. We focus on what are traditionally thought of as ‘cognitive’ practices, but these are analyzed as located within complex cognitive-cultural systems. These problem-solving activities are analyzed as *situated* in that they are viewed as lying in localized interactions among humans, and among humans and technological artifacts and as *distributed* in that they as viewed as taking place across systems of humans and artifacts.

Our research would not be possible without an interdisciplinary team.[2] The studies have been under way for four years and our collection and analysis of the data are ongoing. We aim to develop an understanding of (1) the nature of reasoning and problem-solving in the laboratories, (2) the kinds of representations, tools, forms of discourse, and activities employed in creating and using knowledge, (3) how these support the current research practices and the development of new ones, and (4) the nature of the processes through which new researchers (undergraduate, graduate, postdoctoral) are apprenticed to the work of the laboratory.

BME is an *interdiscipline* in that melding of knowledge and practices from more than one discipline occurs continually, and significant new ways of thinking and working are emerging. Most important for our purposes, 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 cognitive-cultural systems. The characterization as *evolving* adds a novel dimension to the existing literature on environmental perspectives that by and large have not examined these kinds of creative activities. In Hutchins’s studies of distributed cognition in work environments, for example, the cockpit of an airplane or on board a ship, the problem-solving situations change in time. The problems faced by the pilot change as he is in the process of landing the plane or bringing a ship into the harbor. However, the nature of the technology and the knowledge 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 Hutchins documents for the instruments aboard a ship, these are not created and changed in the day-to-day problem-solving processes on board. Thus, these kinds of systems are dynamic but largely *synchronic*. In contrast, in the innovative, creative settings of the research laboratory, although there are loci of stability, artifacts and understandings are created and undergo change and development over time. The technology and the researchers have evolving, *relational* trajectories that must be factored into understanding the system at any point in time. The cognitive-cultural systems of the BME research laboratory are, thus, dynamic and *diachronic.*

Customarily, ethnography has been the primary method for investigating situated cognitive practices in distributed systems. As a method, 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 methodological approach that uses both ethnography and cognitive-historical analysis. On the one hand we conduct cognitive-historical analyses of the problems, technology, models, and humans involved in the research and, on the other, we conduct ethnographic analyses of the day-to-day practices in the laboratory, such as how history is appropriated in their current problem situation.

As a method, ethnographic analysis seeks to uncover the situated activities, tools, and interpretive frameworks utilized 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 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-cultural 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 time, as they unfold in the daily research activities and ground those activities. Cognitive-historical analysis (Nersessian 1992, 1995) enables following 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.[3] Cognitive-historical analysis interprets and explains the generativity of these practices in light of salient cognitive science investigations and findings of mundane cognition. Saliency is determined by the nature of the practices under scrutiny. The objective of cognitive-historical analysis is not to construct an historical narrative. Rather, it is to enrich understanding of cognition in context through examining how knowledge-producing practices originate, develop, and are used in science and engineering domains. 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. Thus we use the customary range of historical records to examine how the problem-solving practices have developed and are used by the BME researchers in and associated with the laboratories. 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.

A central focus of our study is on the technological artifacts that push BME research activity and are shaped and reshaped by that activity. 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. Combining cognitive-historical analysis with ethnography allows us to examine these relationships in situ as they have developed — and continue to develop — in time. Importantly, developing a relationship with an artifact entails appropriating pertinent aspects of its history, which includes the development of the problem situation and what is known about the artifact in question within it.[4] Since these are university research laboratories, the researchers are PhD and MS candidates, undergraduates, and post-doctoral trainees — 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.

Although we are researching three sites, I will focus on one site, 'Laboratory A', a tissue engineering laboratory that has as its ultimate objective the eventual development of artificial blood vessels. The daily research is directed towards solving problems that are seen as smaller pieces on the way to that grand objective. The principal investigator of Laboratory A is a quite senior pioneer in BME and the laboratory has been in existence approximately 20 years. 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 need to be readily available. This requires developing methods and technologies for ensuring cell growth, proliferation, and production.

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 by, 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. Most of the technological artifacts created by the laboratory members are designed to serve this purpose. Cells are stimulated in the in vitro simulation environments, such as the 'flow loop' — a technological artifact created by this laboratory to simulate shear stresses of blood flow in an artery (formally known as a 'channel flow device'). 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.

In addition to and central to the research, the laboratory is a site of situated learning within a community of practice (Lave and Wenger 1991). This particular community, a university research laboratory and an interdisciplinary community focussed on innovation, is a site for learning in various ways. First, it trains students and postdoctoral researchers. The PhD and MS students, in particular, work on projects that evolve into their dissertations and theses, carried out under the supervision of the laboratory director. Second, as an *innovation community*, everyone is learning — director, students, and laboratory manager — continually. Problem-solving on the frontier requires learning in the process. Third, biomedical engineering is an evolving *inter-discipline* — where interactions among concepts, knowledge, and practices from more than one field lead to new cognitive and cultural practices.

There are many dimensions along which to develop the analysis of the laboratory as an evolving cognitive-cultural system. 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 cultural dimensions of scientific and engineering practices. I first develop the notion of the 'laboratory-as-problem-space' in contrast to the traditional notion of the problem space as mentally represented. Then I construe the model-based reasoning used in problem-solving as taking place within the cognitive-cultural systems of the laboratory and not simply within the head of an individual thinker.

The Laboratory as 'Problem Space'

As a cognitive-cultural system the laboratory is not simply a physical space existing in the present, but rather a dynamic *problem space*, constrained by the research program of the laboratory director, that reconfigures itself as the research program moves along in time 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 which comprise people, technology, techniques, knowledge resources, problems, and relationships. Construed in this way, the notion of 'problem space' takes on an expanded meaning from that customarily employed in the traditional cognitive science characterization of problem-solving as search through a mentally represented problem space. The lab-as-problem-space comprises internal and external representations and processes. Researchers and artifacts move back and forth between the wider community and the physical space of the laboratory and so the problem space has permeable boundaries. For example, Laboratory A has created tubular-shaped, bioengineered cell-seeded vascular grafts, locally called 'constructs', that are physical models of native blood vessels. The endothelial cells which the laboratory uses in seeding constructs are often obtained by researchers going to a distant medical school and bringing them into the problem space of the laboratory. Occasionally, the constructs or substrates of constructs travel with laboratory members to places outside the laboratory, such as when one of the graduate students took substrates of constructs to a laboratory at a nearby medical school that has the elaborate instrumentation to perform certain kinds of genetic analysis (micro-arrays). This line of research is dependent on resources that are only available outside the physical space of Laboratory A. The information produced at the medical school is incorporated into the problem space of the laboratory by the researcher, and figures into further problem-solving activities.

We analyze the problem-solving processes implicated in an episode as residing in a cognitive-cultural system comprising both one or more researcher and the *cognitive artifacts* (Hutchins 1995; Norman 1991) involved in the problem-solving episode. Like Hutchins we construe cognitive artifacts as material media possessing the properties of generating, manipulating, or propagating representations. Our approach is to focus on the technology constructed for and used in experimentation. During a research meeting with the laboratory members, including the laboratory director, 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 artifacts to their research. Their classification in terms of ‘devices’, ‘instruments’, and ‘equipment’ is represented in Table 1. Additional ethnographic observations and interviews have led us to formulate working definitions of the categories employed by Laboratory A’s researchers. ‘Devices’ are engineered facsimiles that serve as in vitro models and sites of simulation.[5] ‘Instruments’ generate measured output in visual, quantitative, or graphical form. ‘Equipment’ assists with manual or mental labor.

The cognitive artifacts in the distributed systems of the laboratory cut across the categories, though most are devices or instruments. For example, as a device, the flow loop *represent*s blood flow in the artery. In the process of simulation, it *manipulates* constructs which are *representations* of blood vessel walls. After 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’. In these ways the representations *generated* by the flow loop *manipulations* of the constructs are *propagated* within the system. It is in relation to the researcher(s)’s intent of performing a simulation with the device in order to create new situations that parallel potential real-world situations, and the activity of the device in so doing, that a device qualifies as a cognitive artifact within the system.

Table 1. Sorting of Laboratory A Artifacts by the Laboratory Members

ONTOLOGY OF ARTIFACTS

Devices	Instruments	Equipment
flow loop	confocal	pipette
bioreactor	flow cytometer	flask
bi-axial strain	mechanical tester	water bath
construct	Coulter counter	refrigerator
	‘beauty and beast’	sterile hood
	LSM 5 (program)	camera
	computer	

Certain objects in the laboratory more than others have the power to bind research projects together and to its evolving research agenda. These objects can be thought of as *signature objects* of the laboratory. They are designed or constructed in the laboratory and often play a significant role in the 'initiation' process for new community members. For the classification developed by the laboratory members, we have found that most of these signature objects are the engineered simulation devices. Among the devices currently in use in the laboratory, the flow loop was first created in the research of the director of this laboratory to simulate 'known fluid mechanically imposed wall sheer stress,' in other words to perform as a model of hemodynamics.[6] We have traced aspects of its development since 1985. The vascular constructs were first devised in this laboratory in 1996 as an important step in the overall objective of creating vascular substitutes for implantation. They afford experimentation not only on cells, but on structures more closely related to the in vivo model. The *pneumatic bioreactor* was constructed to 'condition' the tubular constructs, in the hope of strengthening them. At present the constructs are not strong enough to withstand the mechanical forces in the human (or animal) cardiovascular system. This *bioreactor* is used to stimulate the cells mechanically with the objective of changing their mechanical properties. The *mechanical tester*, which subjects the constructs to a unidirectional stretching force, and the *equi-biaxial strain*, which simulates blood vessel expansion and contraction, were created to investigate construct strength.

Devices perform as what laboratory members call 'model systems' — locales where engineered artifacts interface with living cell cultures — in specific experimental problem-solving contexts. These artifacts function as cognitive artifacts through their participation in the reasoning and representational processes of the cognitive-cultural system, but they function also as what cultural studies of science refer to as the 'material culture' of the community. My point is that within the research of the laboratory, they are both, and it is not possible to fathom how they produce knowledge and understanding by focussing exclusively on one or the other aspect. They are representations of current understandings and thus play a role in model-based and simulative reasoning employed in problem-solving; they are central to initiation rites and social practices related to community membership; they are sites of learning; they provide ties that bind one generation of researchers (around five years) to another; they perform as 'ratchets' (Tomasello 1999) that enable one generation to build upon the results of previous generations, and thus move the problem-solving forward. Problem-solving with simulation devices requires that researchers merge concepts, models, and methods of biology and engineering. As such, the devices need to be understood not just as 'boundary objects' (Star and Griesemer 1989) existing in the 'trading zones' (Galison 1997) of two or more communities and mediating communication, but as sites of interdisciplinary melding of concepts, models, methods, artifacts, and epistemologies, where genuine novelty emerges. In sum, they are central in the cognitive-cultural fabric in which creative scientific understandings are produced.

Studying the devices underscores how the kinds of systems we are investigating diverge from those investigated by Hutchins. The devices are not stable technological artifacts, but have a history within the research of the laboratory. Community members need to appropriate aspects of those histories as they apprentice to the laboratory. In their study of learning in communities of practice, Lave and Wenger also noted the importance of history:

> 'Becoming a full participant certainly includes engaging with technologies of everyday practice, as well as participating in the social relations, production processes, and other activities of communities of practice. […] Participation involving technology is especially significant because the artifacts used within a cultural practice carry a substantial portion of that practice's heritage […] Thus, understanding the technology of practice is more than learning to use tools; it is a way to connect with the history of the practice and to participate more directly in its cultural life (Lave and Wenger 1991: 101).

It is important, however, to draw attention to the fact that the laboratories that we have been studying, with their 'mission' to innovate in the area of design with biological materials and systems, are forward-looking communities. In these situations, viewing history as heritage does not suffice. History forms part of the problem space, not as what is usually thought of as heritage, but as a cognitive-cultural resource for moving problem-solving forward. Thus, for example, aspects of the history of a simulation device are appropriated by laboratory members as they learn in apprenticing to the laboratory. Devices will need to be modified, constructed, and reconstructed in the course of research with respect to problems encountered and changes in understanding. One needs to know such things as how and for what purposes a device was built, why it was modified (if it has been), and what worked and did not work for various purposes, so that time and resources are not wasted going down an old path. Laboratory history is present not only in narrative but in the practiced lore that is rehearsed in a configuration of cognitive-cultural practices, including mentoring and constructing.

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 an in vivo model. In order 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 ways to alter it to carry out her project as the new research problems demand, thereby adding to its history. An extended example will serve to illustrate the historical dimension of design and redesign in biomedical engineering research. As noted earlier, the *flow loop* is a highly significant technological artifact in Laboratory A. A crude form made an appearance early in the research and it has been through subsequent redesign to its current form that is shown in Figure 1.

Early experimentation on the vascular system in bioengineering was conducted by the laboratory director and colleagues on blood vessels that were altered while in the living organism. Through surgical interventions blood vessels were made to exhibit pathologic conditions consisting in narrowing of native arteries (stenosis). After sacrificing these animals the

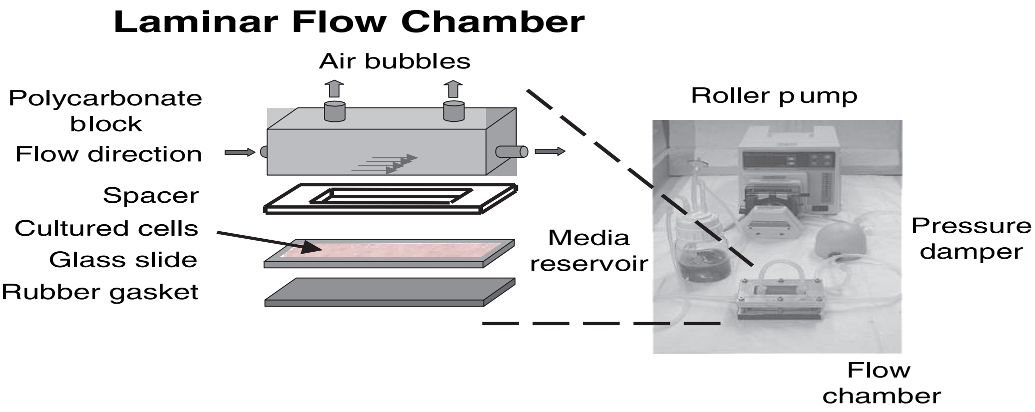

Figure 1. Diagram and Photograph of a Flow Loop

morphology of the cells lining the arterial walls at the pathologically altered regions was studied and quantified in specific aspects (e.g. elongation and orientation of cell filaments). Simultaneously, arterial flow patterns (velocity profiles) were studied for pathologic narrowing with models that replicated the *geometric dimensions* of these observed pathologic regions. These models, which can be called 'replica models', were achieved through casting techniques in which arterial vessels were filled with a fluid plastic and after hardening were used as casts to manufacture a replica of the narrowed vessel. These replica models, individual instances of which were referred to as 'the model', were studied in experimental set-ups that allowed 'flow studies' using laser Doppler studies to determine velocity patterns. The results gained from studying cell morphology and from studying velocity patterns in the replica model were correlated to gain insights into the relations between variations in wall shear stress due to particular velocity patterns (gradients near the vessel wall) and cell morphology of cells lining these vessels. The association of research practices from engineering with practices from biology in this research paradigm began the extended network of interlocking models that would later characterize the workings of Laboratory A, some of which will be discussed in the next section. The elaborate material and measurement practices related to the replica models were rather quickly abandoned, but they launched the director's program of studying the impact of flow in wall shear stresses in vitro with engineered devices that has formed the research agenda of Laboratory A. Simultaneously with the replica studies and the associated cell morphology studies, the director and other researchers had started a line of research with cell cultures of the endothelial cells typically lining the arterial walls. Instead of inducing stenosis in living animals, and thus creating particular flow patterns resulting in particular wall shear stresses, they instead exposed the respective cell type in culture to wall shear stresses by 'flowing' them in a flow channel device. These in vitro experiments on the response of the cells to shear stresses were based on an established fluid dynamic model, specifically, the fluid mechanics of a 'long channel with rectangular cross-section'. In this way, changes in cell morphology (elongation and orientation) could be related directly to known wall shear stresses. Furthermore, the method of measuring velocity patterns in a replica model was now replaced by an engineered artifact of exact geometrical specification, a flow channel. With the controlled flow channel the correspondence between the mathematical and the physical model became an issue of engineering a channel with the appropriate dimensions (in a physiologically meaningful range), rather than measuring velocity patterns using elaborate Doppler laser technology.

The laboratory director summarized for us this earlier period, prior to establishing the practices in their current in vitro form, by saying that it ‘moved [the research] from animal studies to cell culture’ (from ex vivo to in vitro). In the cell-culture line of research an engineered artifact, a flow channel with the accompanying flow-inducing components, served as an in vitro model paralleling certain in vivo conditions of blood vessel pathology that previously were induced in living organisms. The studies using the replica model had in fact dissociated the study of cell morphology from the study of flow patterns, with correlation of their results after the fact. With the flow device the two foci of study were condensed into a single device, in which cultured cells were exposed to flow and thus shear of a well-defined nature. As the laboratory began to establish itself as a cognitive-cultural system, learning to use the flow loop formed an initiation rite experienced by all members. Over time, as new simulation devices appeared within the laboratory, cell culturing took its place as the initiation rite shared by all members, as will be discussed in the next section.

From the outset, redesign has been a central activity within Laboratory A. In working with cultured cells, contamination is a constant problem and this problem was the driving factor in the redesign of the flow channel device. An interview with a former graduate student, now a successful faculty member at another institution, elaborates on this problem and the subsequent redesign.

> So, when I got here in 1994, … the flow chamber was a mess. It was a benchtop system, it had bulky tubes that looked something like some time machine from the 1950s or something […]. Um, but anyway it was quite messy and you know culture studies have to be done at 37 degrees so the way that they would do this was, you know, incubators were certainly around in 1994, uh, they would wrap these coils, these heating coils around these glass reservoirs and because it had to be a set flow, they would use a hydrostatic pressure difference to derive the flow, and uh, a clamp, a regulated clamp to try and regulate the flow through the chamber and out into the uh, into the res, the lower reservoir. So you had two reservoirs, one at the top, and one at the bottom, there’d be a hydrostatic difference between them, and then things would flow and then this whole thing would be sitting on the benchtop uh, big bulky glass reservoirs with bulky tubing and […] And this was subject to about a 50% success rate.
>
> Interviewer: In terms of contamination?
>
> In terms of contamination. And the reason was because this whole thing had to be assembled outside of the hood [colloquial for ‘the sterile workbench’]. There was no way you could assemble this thing to stand up — this thing was on stands — you have to assemble this part outside of the hood, so basically they we would connect these joints here, and connect them outside of the hood. […] Doing experiments

> longer than 48 hours was almost impossible, because at experiments longer than 48 hours the incidence of contamination was probably greater than 90%. Um, but that wasn't really the motivating factor for why I considered changing this design. I actually went to an internship in the first summer that I was here. […] So they [referring to the lab at which he interned] preferred as opposed to heating things, having everything in the incubator. And so when I came back from that internship, … I really like compact designs and I'm always looking for ways […]. I uh, I instituted a lot of the things I saw over there and in our laboratory, and one of the things was model-revising this design to go into the incubator. And uh, that was really why we moved from a system that required heating coils and an upper reservoir and a lower reservoir to a system that was just flow driven with a peristaltic pump and a pulse dampener that was — and everything could be done inside the incubator with smaller tubing, little reservoirs as opposed to big reservoirs.

'Model-revising this design', as the former graduate student described his contribution to this line of research, means to redesign the *physical system* that is the flow channel device, its parts, its set-up, and the physical principles governing its functional design. The actual flow channel, that is the part where liquid flows over the cell cultures, was left untouched in this particular redesign. Since then the flow loop has undergone minor redesign, such as related by a current PhD student. In discussing her own redesign, she started with a discussion of how the researcher just prior to her had modified the flow block to solve some technical problems also associated with bacterial contamination. The modified device that she inherited had previously been used on smooth muscle cells. She now wanted to use the flow loop to experiment with the vascular constructs of endothelial cells, cut open and placed flat for flowing. These flat constructs are thicker than the muscle cells used before, and bumpy. Because of these features, 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 flow in the in vivo model. To begin that research, she, together with another new student, had to redesign the device by changing the width of the flow slit to hold the spacers. Most recently another student planned a significant redesign to enable flowing of constructs in tubular shape in order to accommodate implantation in an '*animal model*' that will be discussed in the next section. This redesign would mark a significant step in the move towards in vivo implantation in that the constructs would not need to be cut open in order to be flowed.

To summarize, redesign of devices in the laboratory is embedded in an understanding of how a certain problem situation has led to the realization of certain design options. In other words, the agenda of redesign characteristic of an engineering research laboratory requires that researchers appropriate some of its history as they learn. The current design is understood to be conditioned on the problem situation as it existed for the laboratory at a prior time, i.e. the cognitive-cultural resources that were available at the time of the respective design's inception and further development, even if these resources and parameters are not fully known to the current researchers. The same holds for the problem that the current design addresses which is perceived as being equally conditioned on this problem situation. Thus, redesign implies constructive and creative involvement with the *historicity of design*. History then is not merely a process that moves us from Time 1 to Time 2 and at Time 2 lets us look back at Time 1. Rather, within the cognitive-cultural systems of the BME laboratory redesign is an *agenda* and with it the historicity of the artifacts becomes a *resource* for novel design options. However, in practice, the historicity of a device or model system is not an immediately accessible resource. We have seen undergraduate researchers in the laboratory for only a semester carrying out their projects with hardly any understanding of the historical dimension of particular designs. Tapping historicity as a resource requires a holistic conceptualization of the laboratory's workings, in other words, of the laboratory-as-problem-space. In the context of the laboratory, the affordances are such that recognition of the historicity of the problem, of the design process, and of its outcome is only of importance if it is intellectually hands-on, that is, can be meaningfully related to working with the respective devices. This is built over time, in the apprenticeships of longer duration undertaken by graduate students and undergraduates who develop long-term research connections to the laboratory.

Distributed Model-Based Reasoning

A division of worlds into in vivo (real world), in vitro (simulated world), and ex vivo (experimental animals that have been modified in some way to make research possible) forms a significant component of the cognitive framework guiding practice in biomedical engineering laboratories. In Laboratory A, for example, since the test-bed environment for developing artificial blood vessels cannot be the human body in which they will ultimately be implanted, the researchers have to design in vitro facsimiles of the in vivo environment and ex vivo implantation environments where experiments can occur. In the research of this laboratory, the mechanisms of the in vivo phenomena are known and thought to be well understood both in biological and mechanical terms. The challenge is to bring together biological and engineered materials with the desired properties so as to perform properly in vivo where those mechanisms operate. The daily in vitro research is directed towards solving problems that are smaller pieces of that grand objective, such as proliferating endothelial cells within the constructs and creating constructs that can withstand the in vivo mechanical forces. The problem space of the laboratory comprises mental models and physical models together with a repertoire of activities in which *simulative model-based reasoning* assumes a central place (Nersessian 1999). Many instances of model-based reasoning in science and engineering employ external representations that are constructed during problem-solving and are central to the reasoning processes, such as diagrams, sketches, and physical models. Diagrams and sketches have been argued to provide constraints and affordances essential to problem-solving that augment and cannot be reduced to those available in whatever internal representations are used by the reasoner during the process (Zhang 1997). Within the cognitive-cultural systems of the laboratory, devices instantiate part of the current community model of the phenomena and allow experimental simu-

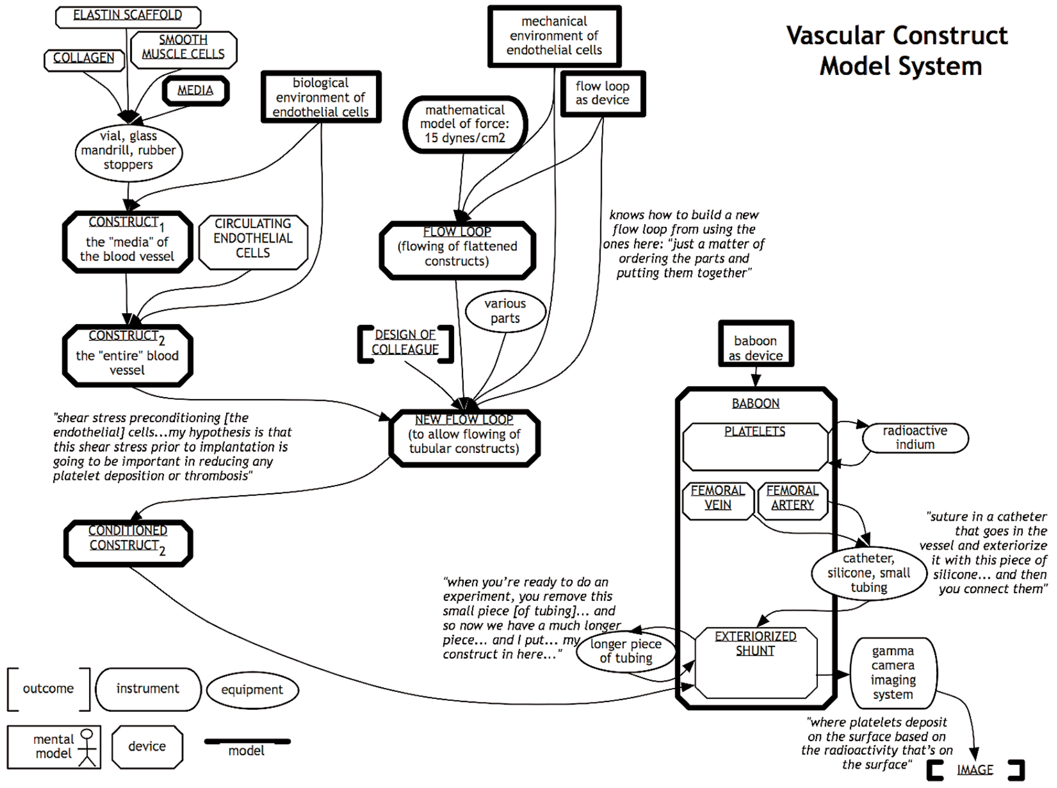

Figure 2.
A Proposed Experiment with a Vascular Construct Model System

lation and manipulation through controlling and screening aspects of the phenomena under investigation. The devices used in Laboratory A are physical models that enable, in particular, controlled simulation of mechanical stresses and strains paralleling those in the body. As a second-year PhD student put it, 'The big, big question is um, how do our constructs act like a modeling tool, how do they respond to — or biological markers respond to — mechanical stimulation.'

Understanding a device as a 'modeling tool' means recognizing both that it models in vivo phenomena and that it is an object in its own right with constraints and affordances — due to the nature of the materials, or the engineering challenges, or some other factors — that need to be taken into account in planning experiments, in making inferences, and in evaluating outcomes. The flow loop, for example, 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.'

The flow loop models shear stress to a first approximation, but the nature of the current design is such that flow is over flat constructs, rather in tubular constructs which more closely approximate blood vessels. In this section

I illustrate distributed model-based reasoning with physical simulation devices through one example of an experiment for which redesign of the flow loop was planned in order to flow constructs in tubular shape prior to implantation in an ex vivo environment. We have diagramed this instance of a vascular construct model system in Figure 2.[7] Calling the reasoning 'distributed' is meant to convey that inference involves manipulating physical and mental models, and thus reasoning processes take place not in the mind of a single researcher, but across researchers and artifacts within the problem space of the laboratory. In this instance, the problem space comprises even the physical space of a research laboratory in another state where the researcher will travel to have experimental access to the baboon or 'animal model'.

Conveying multiple dimensions of the cognitive-cultural systems of the laboratory is a difficult task in the confines of a brief illustration, since it requires providing both thick descriptions and analytical insights. Although we are discussing the practice of simulative model-based reasoning, it is important to keep in mind that models and the practices of using them are both cognitive and cultural achievements. So, though diagram conveys only a pared-down representation of the models in the system, the model system and the proposed experiment are embedded in a rich cognitive-cultural system distributed in space and time, itself designed to enable and support such experimentation. For instance, consider only the segment leading to the creation of the model 'construct2' in the upper left corner of the diagram. As noted earlier, the constructs are bioengineered models of blood vessels that have a history of design and redesign within this laboratory. They occupy a central place in the research since the primary objective is to create from these models a viable substitute artery for implanting in humans. Learning how to culture cells and create constructs is a critical part of the initiation rites for all laboratory members (as noted previously, in the past, the flow loop played this role). The construct is, formally, a '*hybrid, endothelial cell-pre-seeded vascular graft*'. A researcher being apprenticed to the laboratory experiences three forms of engagement and interaction with constructs as her participation and membership in the community grows: (1) making constructs, (2) identifying laboratory members with aspects of research on the constructs, and (3) working with constructs understood as simulation devices.

Making constructs begins with learning cell culturing and maintenance techniques. For the learner, who is an engineer, this is often the first contact they have with biological materials, concepts, and procedures. Cells come from the in vivo world of animals such a pigs and baboons. How much care and maintenance goes into supporting the viability of a cell culture — which the senior researchers refer to as 'babysitting the cells' — amazes and continually frustrates them. Although the gross steps of culturing cells and creating constructs are written down and kept in a book of protocols, the procedures are learned through classical embodied apprenticeship practices. A senior graduate student works closely with a new member in a series of dyadic exchanges that extend over numerous sessions. These sessions are physically intimate in that the intricacies of cell culturing can only be observed at close range with the mentor sitting with arms extended under the sterile hood and the novice hovering close behind and peering over the shoulder of the mentor. This intimate partnership with the mentor provides an initial metaphor for the cognitive partnership the apprentice begins to form with the constructs as simulation devices through which research problems will be addressed (Newstetter et al. 2004). This experience also begins the shift in identity from that of an engineer to an interdisciplinary bioengineer or, as one postdoctoral worker put it to emphasize the heightened salience of biology as her research has progressed, ‘a bio-bioengineer’. While learning to culture cells and make constructs, apprentices explore the research of the laboratory through informal conversations with researchers through which they come to understand how the research of the laboratory largely involves working with constructs as simulation devices. In particular, they identify various researchers with the simulation devices they use in working with constructs, such as the flow loop or the mechanical tester. Within periods of varying length, they identify potential research problems and begin exploring how they might go about solving these using existing devices, redesigning these, and, less often, constructing a new device. The experiment proposed with the vascular construct model system is by a student who entered the laboratory in 2000, designed the model system in the diagram in 2004, and will most likely graduate by the end of 2005.

As noted, constructs are tissue engineering achievements that serve as experimental models in the in vitro world. The objective is to move them back to the in vivo world of human bodies, but the intermediate step is experimental implantation in ex vivo animal models. The diagram in Figure 2 traces the construction, manipulation, and propagation of models within a proposed experiment aimed at solving the problem of reducing platelet formation and, thus, thrombosis. It is a significant experiment in that it is a first move in the direction of ex vivo research. In this case an exteriorized shunt connecting the femoral vein and the femoral artery has been surgically placed in a baboon (with no injury or discomfort to the animal) so that a small amount of blood flow can be diverted through a construct during an experimental process.

Models tend to come in clusters or interlocking configurations, that is, not as isolated entities but rather as standing in particular relationships to other models. The models involved are highlighted by thick lines. The entire model system comprises interlocking physical and mental models within the human–artifact system. Each mental model is both an individual and community achievement. Each physical model is designed by this community to mimic an aspect of the cardiovascular system, for example media and constructs mimic the biological environment of the blood vessel and the new and old flow loops mimic the shear stresses. The proposed redesigned flow loop better approximates the in vivo model because constructs will be stressed in tubular shape, which is necessary for implantation. Note also that models from mathematics and physics form part of the system. The student is still involved in solving her research problem, but the process has been speeded up because, instead of constructing the new flow loop, she realized — on analogy to the shunt created to experiment with the baboon — that plastic tubing could also be connected externally to the input and output of the current flow loop, and that to condition the tubular construct it could be flowed by attaching it to the tubing, as is done with the ex vivo shunt.

As discussed previously, devices not only perform as models instantiating current understanding of properties and behaviors of biological systems; but are also systems themselves, possessing their own engineering constraints that often require simplification and idealization in instantiating the biological system they are modeling. As we have noted, the flow loop *represents* a first-order approximation of shear stresses during blood flow in the artery. In the process of simulation, it *manipulates* constructs, which *represent* the biology and physics of blood vessel walls also to various degrees of approximation. Thus in setting up experiments, making inferences, and evaluating outcomes, researchers are required to have an understanding of the models used in a problem-solving process as a model of the device qua in vitro or ex vivo model and as a model of the device qua device. This entails knowing, for example, along what dimensions the model is abstracted and how and to what extent an outcome could be generalized.

Finally, both physical and mental models participate in distributed model-based reasoning. The researchers in the laboratory call the processes of constructing and manipulating devices ‘putting a thought into the bench top and seeing whether it works or not’. These instantiated ‘thoughts’ (we interpret ‘thoughts’ as ‘mental models’) allow researchers to perform controlled simulations of an in vivo context. 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, 2002) characterized the reasoning involved in simulative model-based reasoning as a form of dynamic mental modeling, possibly employing internal iconic representations. My focus there was on thought experiments in physics, and in that analysis simulative model-based reasoning referred to a mental process. Considering the role of physical simulation devices in problem-solving has led me to recast simulative model-based reasoning as a process of co-constructing and manipulating the researcher’s mental models of the phenomena and of the device and the physical model that is the device, each incomplete. Understood in this way, simulative reasoning would consist of processing information both in memory and in the environment. That is, the model-based reasoning process is distributed in the cognitive-cultural system.[8] Although physical simulations with the model systems are implemented externally relative to the researchers, they nevertheless are integral to the mental models of the researchers by being intended to function epistemically (see also Tweney 2002). Thus, to cast a model — physical or mental — as participating in a *cognitive* process more nearly describes its generative quality, that is, the quality that insight or inference is intended to flow from it (however culturally mediated this generation in fact might be), rather than its locus or medium of operation.

Conclusion

What I have tried to show within the confines of this brief paper is that the complex problem-solving practices of research in science and engineering require that science studies researchers understand and analyze them as forming and being enacted within cognitive-cultural systems. These systems comprise humans, artifacts, and procedures that range from technical to mentoring. A cognitive-cultural system is not a fixed entity, and thus should not be reified. Within the laboratories my research group is investigating, these systems are dynamic, evolving, and continually reconfiguring. Carrying out the project of an integrative cognitive-cultural account of problem-solving in such dynamic systems has required innovation in data collection and analysis. By coupling ethnographic and qualitative methods of analysis, such as grounded coding, with methods of cognitive-historical analysis it is possible to examine in a unified manner the evolution of problems, technologies, models, and learning and the enactment of these in daily problem-solving practices of a community.

Notes

1 I will use 'cultural' as shorthand for 'social, material, and cultural' throughout as a matter of convenience. 'Social', 'cultural', and 'material' are, of course, not coextensive notions and analyses of these dimensions of scientific practice are quite diverse in the literature.

2 This research has been conducted with Wendy Newstetter (co-PI), Elke Kurz-Milcke (formerly a research scientist), and several graduate and undergraduate students. Within our research group there is expertise in ethnography, philosophy of science, history of science, psychology, linguistics, and computer science. We thank our research subjects for allowing us into their work environment and granting us numerous interviews. We gratefully acknowledge the support of the National Science Foundation ROLE Grants REC0106773 and REC0450578.

3 For a comparison of cognitive-historical analysis to other methodologies — laboratory experiments, observational studies, computational modeling — employed in research on scientific discovery, see Klahr and Simon 1999.

4 For an extended analysis of the appropriation of history with the research laboratory, see (Kurz-Milcke et al. 2004).

5 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: 51) introduced and that has been discussed widely in the science studies 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.

6 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!

7 This diagram and several others of model systems used in problem-solving episodes in the laboratory were created by an undergraduate research assistant, Mary Ellen Harmon.

8 For related attempts to recast mental modeling as interactive with the physical environment, 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.

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