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CREATING COGNITIVE-CULTURAL SCAFFOLDING IN INTERDISCIPLINARY RESEARCH LABORATORIES

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THE BIOENGINEERING SCIENCES use a range of resources from various engineering fields and the biosciences to conduct groundbreaking basic biological research in the context of potential application. Pioneering university research laboratories in the bioengineering sciences are dynamic environments in which problems, methods, and technologies are continually undergoing development, and the primary researchers are students developing into full-fledged researchers. Research labs have long been sites for ethnographic research into social, cultural, and material practices of scientific research. Philosophers have only recently been attending to them as sites for developing fine-grained in situ analyses of the exploratory, incremental, nonlinear problem-solving practices of frontier science, their origins and evolution, and the epistemic principles guiding them.

For fourteen years I led a multidimensional, interdisciplinary research project funded by the U.S. National Science Foundation that, in addition to the usual kinds of questions that a philosopher and cognitive scientist might ask about reasoning, representation, problem-solving, and so forth, aimed to glean insights from our investigation of bioengineering sciences research labs to facilitate this kind of frontier interdisciplinary research. University research laboratories are highly significant contexts for making an impact on the research practices of a field because graduate students largely populate them, and these *researcher–learners* develop into the next generation of practitioners over the course of five to six years. In the context of this volume, I interpret "facilitating" as creating structures for research and learning. A premise of our research has been that to create such structures first requires examining the research practices and what already scaffolds them in situ and then collaborating with the faculty researchers on developing scaffolding for learning and research appropriate to their objectives both within the lab and the larger educational ecosystem in which it is embedded. In the investigation discussed here, we had the opportunity to help build that educational ecosystem since there was no standard curriculum in biomedical engineering, and the faculty was engaged in creating a new department with a novel vision of what research in that field should be like.

From the outset we aimed at an *integrated* account of the lab research practices—one that would move beyond the perceived cognitive-cultural divide in science studies (Nersessian 2005). Specifically, because problem-solving processes comprise complex relations among researchers, technologies, and sociocultural practices, we adopted the framework of distributed cognition (d-cog) as a starting point of our analysis. The framework of distributed cognition developed from several strands of critique (see, especially, Hutchins 1995; Lave 1988) of both the context-free, body-independent "functionalist" construal of cognition by experimental psychology and artificial intelligence and the overly linguistic and thing-oriented construal of culture by cognitive anthropology. D-cog is part of a larger movement in the cognitive sciences, which I have called *environmental perspectives* (Nersessian 2005), that is grounded in empirical evidence from a range of disciplines and has persuasively argued that cognition and culture are mutually implicated. Concurring with the notions of cognition as embodied, situated, and enculturated and culture as a process, we framed problem-solving as situated within evolving distributed cognitive-cultural systems (Nersessian et al. 2003). In our case, the plural of the word "system" underscores that the lab and the multiple specific problem-solving processes within it can each be conceived as such a system, with the grain size dependent on the focus of an analysis. Our use of the hyphenated term "cognitive-cultural" is intentional.[1] It stresses that the systems comprising the humans and the artifacts investigated are simultaneously cultural and cognitive systems. The framework of distributed cognition is, itself, in need of development in several directions. On the one hand, as Georg Theiner (2013), among others, has underscored, the cultural dimensions of the framework have remained underdeveloped. On the other, the nature of cognitive contributions by human participants has also been underexamined at the expense of the cognitive affordances of technologies (Nersessian 2009). And, as will be discussed below, expanding the range of problem-solving tasks and environments studied from a distributed cognition framework contributes to further articulating the framework (Chandrasekharan and Nersessian 2015).

Recently, Edwin Hutchins has elaborated on the notion of distributed cognition in an effort to distinguish it from the "extended mind" thesis (Hutchins 2011, 2014). Hutchins stresses first that distributed cognition is not making an ontological claim but rather providing an analytical framework that attends explicitly to the cultural dimensions of cognition. "Distributed" signifies the spatiotemporal *process* nature of culture and cognition, or what he calls a "cultural-cognitive ecosystem" of people, artifacts, and embodied skills (Hutchins 2011, 440–41). Culture and cognition in this view are co-constructed and emergent from the dynamics of complex ecosystems; in our case, the research lab.[2] We contend, further, that the notion of culture-as-process implicates the history of the evolution of the lab in current practices (see, e.g., Kurz-Milcke, Nersessian, and Newstetter 2004; Nersessian, Kurz-Milcke, and Davies 2005).[3] Consonant with the notion of a dynamic ecosystem, we have analyzed both the evolving distributed cognitive-cultural system that is the laboratory and the specific problem-solving processes within it as comprising researcher–learners ("researchers"), technologies, practices, and research problems, all with evolving relational trajectories. As William Wimsatt (Wimsatt 2013b, chapter 1 of this book) points out, the fact that culture is dynamic means that elements will develop and change at different rates, and thus some elements provide *structuring constraints* for future development. As will be developed here, the evolving, historical nature of the system that is a research lab requires adding a new dimension of analysis—how the system builds itself, especially by means of the structuring constraints and affordances of its simulation technologies.

We have studied four labs, two in biomedical engineering (tissue engineering and neural engineering) and two in integrative systems biology (one, purely computational, that collaborates with external bioscientists and the other possessing a wet lab where researchers conduct their own experiments in service of modeling). Although the research in each of these pairs of labs is interdisciplinary, there are significant differences in the *kinds* of interdisciplinarity and thus in existing and needed structures for scaffolding the research of the labs. For this chapter I focus on one of the biomedical engineering labs, tissue engineering (Lab A), to dissect the processes by which problem-solving structure is created through the design of hybrid, bioengineered physical simulation technologies for investigating novel biological phenomena and through the lab's embedding in an educational context that has the goal of designing novel learning experiences to scaffold the development of hybrid biomedical engineers.

THE STUDY

The Interdiscipline of Biomedical Engineering

Biomedical engineering (BME) scientists are a breed of researcher whose aim is to make fundamental contributions to "basic science" and to create novel artifacts and technologies for medical applications. It is often the case that bioscientists have not conducted the basic biological research bioengineers need in order to make progress toward application. Indeed, they might not have even formulated the general problem, such as "what effects are the forces of blood flow having on the cardiovascular system." The basic science research in the labs we studied, such as on shear stresses in vascular biology or on learning in living neural networks, is approached largely from the perspective of engineering assumptions, principles, concepts, and values (Nersessian 2017). Most often, bioengineering scientists investigate real-world phenomena through designing, building, and running models—physical or computational. For engineers, "to engineer" means to conceive, design, and build artifacts in iterative processes. BME researchers extend this notion to making biological ("wet") artifacts through which to carry out research. In the BME labs we investigated, each laboratory engineers physical simulation models, locally called "devices." Devices are in vitro models that serve as sites of experimentation on selected aspects of in vivo phenomena of interest. They are *hybrid* artifacts where cells and cellular systems interface with nonliving materials in model-based physical simulations run under various experimental conditions (Nersessian 2008; Nersessian and Patton 2009). The devices participate in experimental research in various configurations of hybrid "model systems." As one researcher commented, they "*use that [notion] as the integrated nature, the biological aspect coming together with the engineering aspect, so it's a multifaceted model-system.*"[4] In each BME lab, there is one or more *signature* device that plays a central role in evolving the research program. I call such devices "signature" because the lab is usually identified both internally and externally as "the lab that does X (device) studies."

As we will see, signature devices are *generatively entrenched* in that they provide structuring constraints for the evolution of a range of cognitive-cultural practices in the complex system that is "the lab." Jeffery Schank and

William Wimsatt (1986; Wimsatt 1986) introduced the notion of generative entrenchment to emphasize the role of specific entities in evolutionary processes in complex biological systems: "The generative entrenchment of an entity is a measure of how much of the generated structure or activity of a complex system depends upon the presence or activity of that entity. . . . The resulting picture suggests that generative entrenchment acts as a powerful and constructive developmental constraint on the course of evolutionary processes" (33). They also anticipated the potential to extend the notion to other kinds of evolving systems: "Since virtually any system exhibits varying degrees of generative entrenchment among its parts and activities, these studies and results have in addition broad potential application for the analysis of generative structures in other areas" (33). Wimsatt (2007, 2013b) has recently applied it to the role of certain elements in the cultural evolution of a complex system.

Devices, as physical simulation models, are experimental systems designed to function as analogical sources from which to draw inferences and make predictions regarding target in vivo phenomena. They are constructed so that experiments with them should enable the researcher "*to predict what is going to happen in a system [in vivo]. Like people use mathematical models . . . to predict what is going to happen in a mechanical system? Well, this [model system she was designing] is an experimental model that predicts—or at least you hope it predicts—what will happen in real life.*" That is, research is conducted with these in vitro devices, and outcomes are transferred as candidate understandings and hypotheses to the corresponding in vivo phenomena. In effect, the researchers build parallel worlds in which devices mimic specific aspects of phenomena they cannot investigate directly due either to issues of control or ethics. In the philosophical literature on models, "simulation" is customarily reserved for computational modeling. However, respondents in our investigation variously use "simulate" and "mimic" in explaining how their physical models perform as they are "run" under experimental conditions. It is the dynamic nature of the models that makes them simulations. Thus, we use "physical simulation model" to refer to such bioengineered devices. Simulation by means of devices is an epistemic activity that comprises open exploration, testing and generating hypotheses, and inference. In our analysis, simulation devices are loci of integration of cognition and culture. They simultaneously constitute the "material culture" of the community, give rise to social practices, and perform as "cognitive artifacts" in their problem-solving practices. Understanding how these communities produce knowledge requires examining both aspects.

Early in our investigation, one researcher characterized the practice of building and experimenting with devices as "*putting a thought into the benchtop and seeing whether it works or not.*" With respect to a researcher, as an instantiated thought, the device is a physically realized representation with correspondences to the researcher's mental model. As a tangible artifact, it evolves along with the researcher's understanding developed in the experimentation that the artifact makes possible. As a representation, it refers both to the in vivo phenomena and to the researcher's mental model. As such, the artifact is a site of simulation of not just some biological process but also the researcher's current understanding. The notion of "*the experimental model that predicts*" we encountered above is a distributed model-based reasoning system comprising researchers and simulation models. The "cognitive powers" created by constructing physical simulation models include enhanced ability for abstraction, for integrating knowledge and constraints from diverse domains, for conceptualization, and for changing representational format in ways that afford analogical, visual, and simulative reasoning (Nersessian 2008, 2009). Investigating scientific practice in the wild enables us to discern facets of how these powers are created in situ within the developing and evolving material and sociocultural environment.

BME labs can be cast broadly as what Karin Knor Cetina (1999) has characterized as *epistemic cultures.* These "are cultures that create and warrant knowledge" (1). Whereas the notions of discipline and specialty typically refer to the "differentiation of knowledge" and thus to the institutional organization of knowledge, epistemic culture shifts the focus of attention to "knowledge-in- action" (Cetina 1999, 3). As an approach to the study of science, the notion of an epistemic culture serves to focus on the differences of "knowledge-making machineries" in different subcultures. As Cetina details through case studies of experimental physics and molecular biology practices, these machineries comprise sociocultural structures as well as technologies of research. The analysis of epistemic cultures typically does not attend to the differences in epistemological assumptions underlying the practices of knowledge-making subcultures, which are important when considering interdisciplinary cultures since these assumptions often clash. As Evelyn Fox Keller has pointed out, there are differences in "the norms and mores of a particular group of scientists that underlie the particular meanings they give to words like theory, knowledge, explanation, and understanding, and even to the concept of practice itself" that are equally significant for individuating subcultures and understanding their practices (Keller 2002, 4). Accounting for the research in the labs we investigated requires both attending to the devices qua machineries of making knowledge, located in environments of "construction of the machineries of knowledge construction" (Cetina 1999, 3), and the devices qua artifacts that embed, and through which one can begin to discern, the epistemological assumptions, norms, and values of the culture of BME and its subdivisions (e.g., tissue and neural engineering).

In any analysis, researchers need to consider what constraints devices possess deriving from their design and construction (device qua device) and what limitations these impose on the simulation and subsequent inferences and interpretations (device qua model). Further, there is a tension between constraints on the design and functionality of a device (qua device) that derive from biology and from engineering. One respondent provided an example of this tension in the context of a problem in which the cells of a researcher kept dying in a simulation device, even though all the environmental conditions of media, temperature, and incubation seemed appropriate for sustaining them. The problem turned out to be the material from which the chamber holding the cells was built. As he recounted, "*His device was something he created and built based on the mechanical properties. But in the design process he did not take into account that maybe some of the materials used to build his device were toxic [to cells].*"

From a d-cog perspective, a device also has a dual nature: It serves as a site not only for the simulation of biological processes (machinery) but also for the researchers' understanding, epistemic norms, and epistemic values (model). The design of a device embeds norms and values primarily associated with the kind of quantitative analysis aimed at by engineers rather than biologists, such as approximation and simplification. Many of the researchers we interviewed characterized this difference as biologists focus on how "*everything interrelates to everything else,*" while engineers "*try to eliminate as many extraneous variables as possible so we can focus on the effect of one or perhaps two, such that our conclusions [qua model] can be drawn from the change of one variable.*" An overarching problem of the labs we studied is to determine the appropriate or best feasible abstraction of the in vivo phenomena to address their research questions. For instance, the endothelial cells lining an artery experience turbulent blood flows in vivo, but from an engineering perspective, it is desirable to begin with a first-order approximation (laminar flow).

Framing the lab activities as situated in complex cognitive-cultural systems provides a means of analyzing the problem-solving processes in a manner that integrates cognition and culture (Nersessian 2006). However, this analysis cannot be done simply by applying the current framework of d-cog (Hollan, Hutchins, and Kirsh 2000; Hutchins 1995; Kirsh and Maglio 1994). That framework was developed through studies of highly structured, dynamic problem-solving environments (plane cockpit, naval ship) in which participants carry out largely routinized tasks using existing technologies (such as the speed bug or the alidade), and the knowledge the pilot and crew bring to bear in those processes is relatively stable, even in novel situations. In contrast, the BME research lab is an innovation community where researchers often do not have established methods, technologies, and well-defined problems prior to beginning the research. Although loci of stability provide structuring constraints, equally important features of these labs include the evolution of technologies and the development of the researchers as learners in the processes of carrying out an overarching research agenda. The technological components of the research lab, for instance, evolve in unanticipated ways. We witnessed several cases in which the researcher had to design and construct new or redesign existing simulation devices in the course of problem-solving. At each slice in time, “the lab” comprises the current state of devices and research problems, students at various points of development into researchers, and a lab director at a stage of his or her research program. In effect, the lab *builds itself* as a cognitive-cultural system with specific affordances and limitations for problem-solving as it creates knowledge (Nersessian 2012). Examining how the lab builds itself provides significant insight into how researchers “create their cognitive powers by creating the environments in which they exercise those powers” (Hutchins 1995, xvi). We focus on designing and constructing physical simulation models because they are a major means through which engineering scientists build cognitive powers (Chandrasekharan and Nersessian 2011; Chandrasekharan and Nersessian 2015; Nersessian 2012).

University research labs are significant sites of learning, populated primarily with graduate students and, increasingly, undergraduates. It is a remarkable feature of BME labs that graduate students are simultaneously learners and pioneering researchers. Thus, the development of researchers as learners is a significant component of the evolution of the lab. Our labs reside in a BME community that places high value on what it calls "interdisciplinary integration" at the level of the individual researcher. For them this means moving beyond problematic collaborations that stem from the numerous differences between the practices and epistemic values of engineers and bioscientists, to the extent possible, and cultivating the individual researcher as a hybrid biomedical engineer from the outset, such as when the novice engineer learns to harvest and cultivate the cells she needs for research. The nature of the research requires lab members, who arrive predominantly with engineering backgrounds, to develop equal facility with wet-lab techniques, as well as engineering design and a selective deep knowledge of the biology of their research targets. These communities see themselves as cutting-edge, frontier researchers. The lab ethos is infused with an open-ended sense of possibility, as well as a tinge of anxiety about how little is known in their area and whether PhD research projects will work out. The researchers place a high value on innovation in methods, materials, and applications. Failure is omnipresent, as are lab-devised support structures for dealing with it. The social structure in each lab is largely *nonhierarchical*—a feature that in this case we attribute to the frontier and interdisciplinary nature of the research, where no one (including the director) considers herself or himself *the* expert, and requisite knowledge is distributed across the lab and wider community. Opportunities to innovate are provided to everyone, including a freshman who might have an interesting idea. In the period during which we conducted our investigation, we saw several instances in which "big gambles" led to high payoffs, sustaining this attitude, despite the fact that most of the researchers engaged in high-risk research were doing it for their dissertation projects. Projects can always be modified and scoped down to what is feasible in the time allotted. The sociocultural fabric each lab, and the community as a whole, builds has been highly successful in helping students to graduate and preparing them for excellent positions in academia and industry.

Method: Cognitive-Historical Ethnography

Our research group conducted an ethnographic study that sought to uncover the activities, artifacts, and sociocultural structures that constitute research as it is situated in the ongoing practices of the Lab A community.[5] We conducted two years of intensive data collection, followed by two years of targeted follow-up and, thereafter, limited tracking of students through to their graduation. We took field notes on our observations, audiotaped unstructured interviews (72), and video- and audiotaped research meetings (17). As a group (four ethnographers), we completed an estimated four hundred hours of field observations. Our "team ethnography" approach supplanted videotaping research activities in the lab. Although we were allowed to videotape research meetings, it did not prove feasible to videotape research as it was taking place. We used interpretive coding in analyzing interviews and field notes. Broadly consistent with the aims of "grounded theory" not to impose a specific theoretical perspective on the data (Glaser and Strauss 1967; Strauss and Corbin 1998), we approached coding to enable core categories and interpretations to emerge from the data and remain grounded in it while at the same time remaining guided by our initial research questions. We then developed case studies of specific researchers and deeper analyses of themes that had emerged from the data that were relevant to our research questions. We also examined findings with respect to pertinent philosophical, cognitive, and sociocultural theoretical frameworks.

Additionally, since these labs are evolving systems that reconfigure as the research program moves along and takes new directions in response to events occurring both in the lab and the broader community, there is a significant historical dimension to our analyses. As noted previously, the signature technologies of the cognitive-cultural systems are designed and redesigned in the context of research problems and projects, new methods are developed or adopted, and at any slice in time, the lab is populated by students at various points in their development into full-fledged researchers. To capture the historical dimension of these lab communities, we used interpretive methods of cognitive-historical analysis (Nersessian 1987, 1995, 2008). Coupling ethnography with cognitive-historical analysis affords examining how history is appropriated in the social, cultural, and material dimensions of practices, as these currently exist.

Specifically, cognitive-historical analysis enables following the trajectories of the human and technological components of a cognitive system on multiple levels, including the physical shaping and reshaping of artifacts in response to problems, their changing contributions to the models developed in the lab and the wider community, the nature of the concepts that are at play in the research activity at any particular time, and the development of learners as researchers.[6] Our cognitive-historical analysis uses the customary range of historical records to uncover how Lab A researchers have developed and used representational, methodological, and reasoning practices, as well as the histories of the research technologies. These practices can be examined over time spans of varying length, ranging from periods defined by the activity itself to decades or more.[7] In this context, the objective of cognitive-historical analysis is not to construct a historical narrative. Rather, it is to enrich our understanding of the cognitive-cultural system through examining how knowledge-producing practices originate, develop, and are used.

Making sense of the day-to-day practices and detailing the histories of researchers, artifacts, and practices are prima facie separate tasks. However, the research process within the labs we studied evolves at a fast pace, which necessitates integrating the two endeavors. With respect to the devices in particular, the ethnographic study of how they are understood and used by various lab members, coupled with ongoing interviews around research and learning, allows us to conjoin the cognitive-historical study of the developing lab members, the lab artifacts, and the lab itself, with an eye to the lab members' perception of these. Of particular note is our finding that device history, which chronicles the development of the current problem situation and what is known about the artifacts in question, is often appropriated hands-on. Since devices, inherited and new, need to be (re)designed for the current problem situation, avoiding past pitfalls requires, among other things, knowing why and how a certain problem situation has led to the realization of certain design options. The historicity of the artifacts becomes a resource for novel design options, though in practice it is not an easily accessible resource. However, it becomes more available as a researcher's membership in the community develops.

In the following sections, I will examine how the devices of Lab A provide not only scaffolding for current problem solving, but also create structural constraints and affordances for research potentialities not yet envisioned, and in so-doing build "the lab" itself. I will then discuss the wider ecosystem that has been "engineered" to provide scaffolding for researcher-learners to develop into the hybrid biomedical engineers envisioned to populate and build a novel twenty-first century version of the field of BME.

CREATING COGNITIVE-CULTURAL SCAFFOLDING: THE LABORATORY FOR TISSUE ENGINEERING

The laboratory for tissue engineering (Lab A) dates from 1987, when the director moved to a new university for the opportunity to begin research in the emerging area of tissue engineering. During our investigation the main members included the lab director, the lab manager, one postdoctoral researcher, seven PhD students, two master of science students, and four long-term undergraduates.[8] Several other undergraduates visited for a semester or a summer internship. Of the graduate students, two were male and seven were female, as was the postdoctoral researcher. All of these researchers came from engineering backgrounds, mainly mechanical or chemical engineering. The lab manager had a master's degree in biochemistry. The laboratory director's background was in aeronautical engineering, but he was by then a senior, highly renowned pioneer in the field of BME and the emerging subfield of tissue engineering.

Starting in the mid-1960s, the now director of Lab A had worked as an aeronautical engineer for the space program on how the effects of vibration along the axis of the Saturn launch vehicle *(pogo stick vibration)* affected the cardiovascular system of astronauts. He developed the hypothesis that the physical forces to which blood vessels are naturally exposed, such as pressure and forces associated with blood flow through the arteries, could adversely affect the blood vessels and thus be implicated in disease processes such as atherosclerosis. He embarked on a program of research into how and under what conditions the physical forces might create disease through *arterial shear* forces.

Building Simulation Devices and Model Systems

The future Lab A director decided early in this research to focus his efforts on the endothelial cells that line the arteries: "*It made sense to me that if there was this influence of flow on the underlying biology of the vessel wall, that somehow the cell type had to be involved, the endothelium.*" In the 1970s vascular biologists were focused on biochemical processes, and those he contacted were skeptical of the hypothesis. As a result, he ended up in the laboratory of a veterinary physiologist, where they surgically created animal models to induce pathologies in native arteries to investigate the nature and effects of arterial shear. Problems of control were significant in these modeling practices and led him to set out on a program of in vitro research that would require developing physical models through which to simulate biological phenomena with the desired experimental control. Thus, nearly all problem-solving activities in Lab A are model-based, in the sense that they require building (designing, constructing, redesigning) physical models, assembling them in various model-system configurations, and performing simulations under a variety of controlled experimental conditions.

The initial configuration of Lab A revolved around one physical model, the flow channel device, or *flow loop,* which is designed to enact selected in vivo blood flow conditions, normal and pathological. It consists of a flow channel (designed in a physiologically meaningful range) with accompanying flow-inducing components (such as a peristaltic pump, a pulse dampener, and liquid the viscosity of blood) designed to represent to a first-order approximation shear stresses that can occur during blood flow in an artery. It formed a model system with endothelial cell cultures on slides. When cells mounted on slides are "flowed" under different conditions, changes in cell morphology and proliferation can be related directly to the controlled shear stresses. This device started its life as a large, cumbersome artifact on a stand, for which contamination was a constant problem since it could not be assembled under the sterile workbench hood. Within a few years, it was re-engineered into a compact design that fits under the sterile hood, and experiments can be run in an incubator. This redesign process was chronicled for us in an interview with a recent graduate of the lab (see Kurz-Milcke et al. 2004).

After several years of research, the lab sought a better model system. Using cell cultures on slides provides only a limited understanding of arterial shear stress. Specifically, as the director noted, "*Putting cells in plastic and exposing them to flow is not a very good simulation of what is actually happening in the body. . . . If you look within the vessel wall you have smooth muscle cells and then inside the lining is [sic] the endothelial cells, but these cells types communicate with one another. So we had an idea: let's try to tissue-engineer a better model-system for using cell cultures.*" The idea was to create "*a more physiological model,*" where the effects of shear could be studied on more components of the blood vessel wall than with the endothelial cells in isolation. In principle this should help to better understand the functional properties related to arterial shear. To expand the possibilities for studying these properties, the director took "*the big gamble*"—to create a model of the blood vessel wall constructed from living tissue. If they were successful in building this model, it would open the possibility of turning it into a vascular graft for repairing diseased arteries. This model is variously referred to within the lab as the "construct," the "tissue-engineered blood vessel wall model," and, underscoring its application potential, the "tissue-engineered vascular graft." The flow loop and construct were the signature devices of the lab at the time of our investigation.

When we entered the lab, the construct was the focal simulation model. Because all the researchers would need to build their own constructs, cell culturing had supplanted learning the flow loop as the initial entry point into the lab culture. Learning to culture cells (bovine or porcine), as a senior researcher told us, is a "*baseline to everything*." Whereas learning to manipulate the flow loop is a relatively easy task for an engineer, learning to culture cells and create constructs is not. The consequences of failure are high: when cell cultures die, experiments are ruined. As a result, much mentoring took place around learning to culture cells, starting with harvesting them from arteries donated from an animal lab at another institution. Although there are written protocols for the steps, we witnessed that these are learned in embodied apprenticeships over numerous sessions, first by hovering in close physical proximity as the mentor conducts the procedure under the sterile hood and then by the novice trying them herself. The discourse of the lab frequently centers on keeping the cells "happy," calling them "pets," bemoaning long weekends "babysitting" them, and sharing war stories about facing the recalcitrance of cells to respond in ways they desire. Novice researchers start to build up both tacit experimental know-how and resilience in the face of failure through this extended mentoring process.

Simultaneously, learning how to culture cells provides entre into the problem space and cognitive practices of the lab. Cell culturing is a prelude to building the construct models needed for most research projects. The in vivo blood vessel comprises several layers, and the in vitro construct device constitutes a family of models that can be built with different levels of approximation for simulating in vivo processes. The novel application goal that the construct gave rise to for Lab A—to tissue engineer a viable replacement blood vessel for human implantation—created the need to design and build other simulation models. To be either a functional model or an implant requires (among other things) that the cells embedded in the scaffolding material replicate the capabilities and behaviors of in vivo cells in order to achieve higher-level tissue functions, such as expressing the right proteins and genetic markers. Further, a vascular implant needs to be strong enough to withstand the in vivo blood forces. These problems, in turn, opened new lines of lab research and led to building new devices and model systems through which to manipulate and examine construct properties under various conditions. For example, the lab developed two devices to simulate mechanical forces (the pulsatile bioreactor and the equibiaxial strain device) and

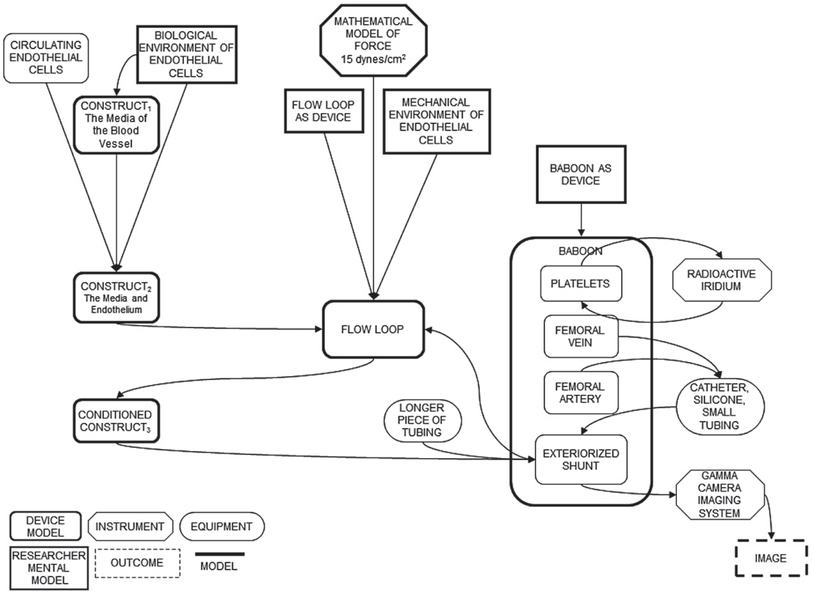

Figure 3.1. Partial vascular construct model system.

an "ex vivo" animal (baboon living in another lab) model system to investigate whether progenitor cells develop the ability to express anticoagulant proteins in response to shear (as do mature in vivo endothelial cells). A partial depiction of this animal model system (Figure 3.1) serves to illustrate how the distributed system *interlocks* a number of models, physical and mental.[9] It is "partial" because it can be extended out into a complex fabric of additional models and researchers that contribute to its functioning as a model-based reasoning system, through which inferences about the in vitro and the in vivo phenomena are made.

Building out the Cognitive-Cultural System

A glimpse of Lab A as a distributed system is provided in the representation created when we asked the director to draw a picture of the current lab research partway though our study (Figure 3.2). We gave no instructions for how to do this. His stated intention was to depict how his research "barriers" *(top section),* researchers *(middle section),* and technologies *(bottom section)* are interconnected. The diagram on paper is static, but the director's representation can be interpreted as providing a schematic of "the lab as an

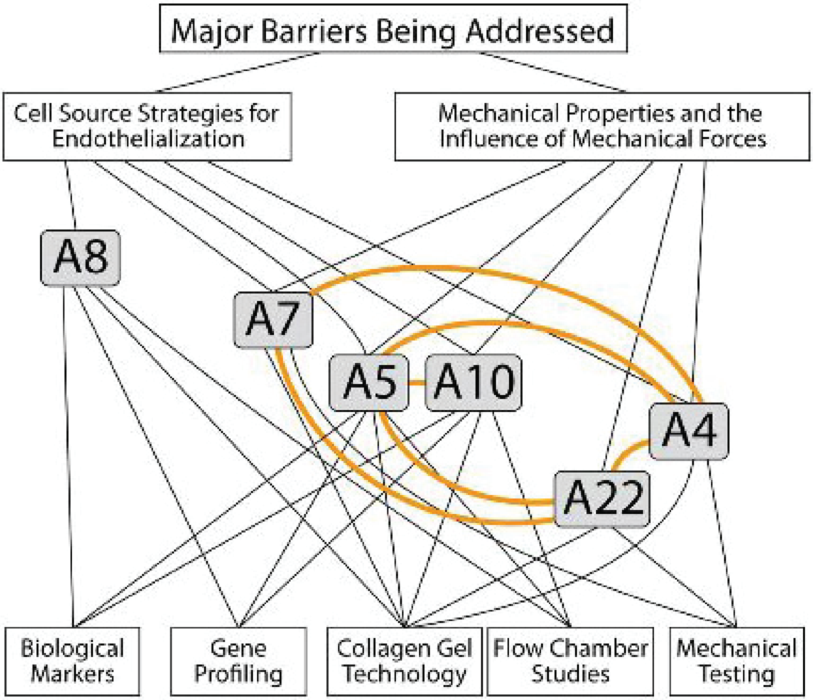

Figure 3.2. Lab A director's representation of the lab's research.

evolving distributed cognitive-cultural system"—a dynamic constellation of interrelated problems, researchers, simulation models, and other technologies. Although the director did not include himself on the diagram, he was, of course, an integral part of the system even though his visits to the physical space of the wet lab were rare. He spent a significant amount of time on the road promoting the research and obtaining funding, in addition to administering an interdisciplinary center. I next outline, briefly, how this system formed and evolved in the course of addressing the research problems through numerous iterations of designing, building, and experimenting with physical simulation models.

At the top of the diagram, the director categorized the "major barriers" with which the research dealt. From discussion with him about the diagram, it became clear that "barriers" are "addressed" by formulating and pursuing research problems that interconnect the basic biological research of the lab and its medical application aim. To address the barrier of "mechanical properties and the influence of mechanical forces" requires formulating research problems directed toward understanding the nature of arterial shear and its role in normal and disease processes. Solving these problems would further the application goal by bringing the research closer to creating an implant with the requisite mechanical properties to function within the body, such as shear strength. To address the barrier of “cell source strategies” requires research directed toward the problem of providing endothelial cells (among the most immune sensitive in the body) for a viable implant that would not be rejected by the recipient’s body. This problem, in turn, opened lines of basic research for the members, such as the role of forces in stem cell differentiation (A8) and in the maturation of progenitor cells (A7).

The lab-built simulation models are designated by “collagen gel technology” (construct), “flow chamber studies” (flow loop), and “mechanical testing” (pulsatile bioreactor and equibiaxial strain device). The kinds of investigations along the bottom of the diagram implicate both the lab-built simulation models and the technologies through which simulation outcomes are examined. For instance, after a flow chamber study in which the construct would be subjected to controlled shear stresses (“conditioning”), the effects on the endothelial cells can be examined for various biological markers or gene profiling, which implicate a range of technologies, some external to the physical space of the lab, such as the confocal microscope to study morphology and migration or DNA microarray technology, used for studying gene expression. Also, “mechanical testing” implicates a lab-built instrument for testing the mechanical strength of a construct after conditioning.

The director intended that thick lines denote interconnections among the individual research projects with respect to the researcher designated to build the animal model system that would integrate these projects (A7). A postdoctoral researcher (A8) is represented as unconnected to the students because she started a new line of lab research into the possibility of stem cell differentiation by means of mechanical forces as a source of endothelial cells for the construct that only later (after success) became more central to the research. She did interact with other lab members about her and their research during conversations in the course of lab activities and at lab research meetings. Although research projects were carried out by individual lab members (sometimes assisted by an undergraduate or master of science student), we witnessed joint problem-solving episodes within the lab and during the lab meetings (held at varying intervals when the director was in town). Each individual research project and the problem-solving processes associated with it can be explicated as performed by a distributed cognitive-cultural system. But the lab's dual problems of understanding the effects of arterial shear and creating a viable implant built the lab itself into an evolving system that afforded and constrained the individual research. The diagram depicts the interconnected subsystems that contribute to building out the lab-as-distributed-cognitive-cultural-system.

When the researchers noted in Figure 3.2 entered the lab, the flow loop model was a well-established technology of research, but several formulated research problems that required some redesign of it. The construct model was a recent development, and all the researchers played significant roles in furthering its design in directions related to their specific projects. A5's research was directed toward correlating the development of arteriosclerosis with the genetic behavior of the endothelial cells and progenitor endothelial cells that circulate in the bloodstream by simulating various flow conditions. A10's research was investigating the effects of shear stress on aortic valve function, using valvular endothelial cells with a novel aortic construct that he designed. Mechanical integrity and strength were primary concerns for him, and, although he ended up not using it himself, he designed and built a new device for the lab: an equibiaxial strain device that simulates the strain (deformation from stress) experienced by vessels as blood flows through them (Nersessian, Kurz-Milcke, and Davies 2005). Components of it would be put to surprising use by a future researcher investigating stem cell differentiation (Harmon and Nersessian 2008). A4's research was to examine specific biological markers in relation to the controlled mechanical stimulation of constructs, as compared with their behavior in native tissue. A22's research focused on improving the mechanical strength of constructs. And, all of these projects are layers that undergird the baboon model system designed by A7 for the ex vivo experiment (Figure 3.1), intended to bring them closer to the medical application goal.

As indicated by the thick lines on the diagram, all of the system's components are connected to A7, who in an early interview noted that she had been designated as "*the person who would take the construct in vivo.*" This meant that she would need to create a model system in which a construct would be connected to the vascular system of a living animal. To be successful, the project would need to "*obviously integrate the results of colleagues here in the lab.*" At the start, she was quite unclear about just what she would study with the model. Once she decided on a specific animal, a lot of time was devoted to designing a means of connecting the fragile construct to the animal without it rupturing (and in a humane way). Her research project evolved into investigating whether shear stress conditioning of endothelial progenitor cells with the flow loop would make them function as mature endothelial cells in the production of thrombomodulin (a protein that prevents platelet formation) when attached to an animal circulatory system. For her investigation she designed a model system that could connect the construct to the bloodstream of a baboon by means of an exterior shunt between the femoral artery and the vein of the animal. The ex vivo simulation was designed to be run in real time through a gamma camera to provide functional imaging. Figure 3.1 provides a partial representation of this model system. Designing and running this model system with the requisite experimental controls was the most complex problem undertaken by the lab to date. As A7 noted, "*In the lab we can control . . . exactly what the flow is like. . . . But when we move to an animal model, it's more physiologic—the challenge then is that is a much more complex system.*" Despite the complexity, she was able to determine that preconditioning with flow loop shear at the normal human in vivo rate of arterial shear (15 dynes/cm^2) enhances the ability of progenitor cells to express anticoagulant proteins within the model system. This finding made a significant contribution to both the research community's understanding of the effects of arterial shear and the problem of endotheliel cell sources for implantation (see Nersessian 2009).

Discussion: Evolving the Cognitive-Cultural System

The few details of Lab A practices sketched in this chapter provide an illustration of how the devices that researchers build in the course of specific problem-solving efforts in a lab also participate in building and evolving a complex distributed cognitive-cultural system. These artifacts provide structuring constraints that create potentialities that researchers can exploit to evolve the system further. At the outset, this lab director did not envision his lab engaging in tissue engineering to make vascular construct models or conducting stem cell research and gene profiling. The initial understanding of arterial shear stemmed from his early mathematical modeling of vibratory forces on the human vascular system and experimental modeling with animals. The limitations of in vivo research with animal models led to taking the research in vitro, which afforded more control and opened the possibility of examining selected features of arterial shear in relation to endothelial cells. Building the flow loop model enabled them to focus largely on the structural properties and the proliferation behavior of cells under shear. But after several years of experimenting with endothelial cells, he realized the flow loop also offered the possibility of examining the relationships among different kinds of cells in the blood vessel wall if they could engineer a living three-dimensional model. Designing the construct family of models provided not only a range of more physiologically accurate models but also the potential to create a vascular graft for human implantation. Importantly, it afforded the possibility of investigating the functional properties of blood vessels in relation to shear (including building several new devices), which in turn led to the lab's ability to create a completely different kind of animal model system from those of the director's initial research. In sum, building physical simulation models has provided a platform for articulating a cognitive-cultural system comprising researchers, problems, models, technologies for experimentation, visualization, and analysis, and sociocultural practices that constitute Lab A as it evolves over time.

This brief glimpse of the evolving cognitive-cultural structures that enable research in Lab A calls into question the classic notion of a scaffold as something that falls away after it has served its purpose; cognitive-cultural scaffolding is *incorporated* into the evolving distributed cognitive-cultural system. The evolving technologies and researchers are interwoven into the fabric that *is* the system. This conception of scaffolding is exemplified by the construct model itself. The tissue-engineered vascular graft is built on a collagen scaffold that is incorporated into the fabric of the constructed vessel. The engineered vessel, if successful, would be incorporated into the in vivo vascular system. The notion of generative entrenchment helps to articulate this notion of scaffolding as incorporation in the evolution of the cognitive-cultural system of a research lab. Signature devices, in particular, and the cognitive-cultural practices associated with them provide constraints and affordances for evolving the research of the lab. They contain the potential for the development of future cycles of design and redesign, which often proceed in novel and unanticipated ways.

In an important sense, the core activity of the lab is building itself as a distributed cognitive-cultural system directed toward achieving the overarching goals of the research. The initial and persistent goal of Lab A has been to understand the role of physical forces on biological processes in the vascular system. The flow loop is particularly generatively entrenched in that it has served as an integral part of the research of the lab for all the years of its existence. It made possible taking the research in vitro because normal and pathological in vivo forces on cells could be replicated to a first-order approximation—and potentially could be redesigned for higher-order effects if necesssary. Its generative entrenchment can be seen on two levels. On a metalevel, through its design and use it has entrenched the practice of importing engineering concepts and methods of analysis pertaining to mechanical forces into the study of biological phenomena. On a physical level, as a device it has formed a component of most experimental model systems (see, e.g., Figure 3.1). Most importantly, its affordances and constraints led to the formation of new problems and novel technologies. The kinds of experimentation the researchers envisioned could be done with the flow loop led, for instance, to the novel construct family of models. The construct model needed to be designed to interlock with the flow loop in experimental situations, some of which, in turn, required modifications to its design. As we saw, the construct model provided the lab with a more physiologically realistic model. That, plus the potential it provided for a novel application, generatively entrenched the construct in the research program, thereby opening further lines of research, which led to the lab building several new simulation models and incorporating new technologies into its analyses.

Although I have focused on the hybrid simulation technologies, this analysis of Lab A as an evolving distributed cognitive-cultural system is, importantly, incomplete without at least briefly outlining, at the institutional level, the coevolution of educational cognitive-cultural scaffolding specifically developed and directed at creating a new kind of interdisciplinary researcher in BME—one designed toward evolving the research field beyond the problematic collaborations of researchers in different disciplines by creating hybrid BME researchers.

CREATING SCAFFOLDING FOR BME RESEARCHERS AS LEARNERS

University labs are populated largely by students, and the lab context and wider research communities are not sufficient to provide the cognitive-cultural scaffolding for students to develop fully as researchers. The Lab A director and other senior colleagues saw as their challenge the design and building of a new educational environment for developing their students into a new breed of researcher. This new breed would move beyond their own experiences of being educated as engineers who later moved into biomedical research by being educated as hybrid biomedical engineers from the outset. As a consequence they determined they would develop a pioneering educational program that would firmly establish BME as an “interdiscipline” that integrated all three components in its research and education.[10] The graduates of this program would be able to move into academia, medicine/public health, industry, or government and fluently collaborate with other hybrids or with disciplinary colleagues, thus mitigating much of the "interactional complexity" of interdisciplinarity (Wimsatt 1972). This was an explicit decision that had three main components: (1) two new buildings with architecture designed to promote interdisciplinarity among bioengineering, biosciences, and medicine, with one building dedicated entirely to the envisioned BME department; (2) a new joint department of BME across two universities with one university providing largely engineering expertise and the other medical expertise, with the biosiences drawn from each and with several new faculty lines for young hybrid researchers; and (3) a new educational program (starting at the graduate level but quickly adding an undergraduate degree) that would integrate the three components of the field throughout its curriculum and cultivate student identities as biomedical engineers. Together, these components would serve to articulate and institutionalize the kind of interdisciplinarity they broadly envisioned—hybridization (Gerson 2013; Wimsatt 2013b).[11]

When we became involved, the first two components were well underway and provided the institutional and material structures from which to develop an educational program. They had few ideas about how to construct an educational program, but in their estimation, there were no established curricula or textbooks that could be adapted to achieve their vision. Through a serendipitous circumstance, they became interested in understanding what cognitive science might have to offer as a resource. At that time the U.S. National Science Foundation (NSF) had a requirement that any grant that included an educational program also had to include a cognitive science dimension. The leaders of the BME initiative were applying for an engineering research center that would include graduate training. I was director of the program in cognitive science, so they contacted me and asked if I could explain why the NSF would have such a requirement (i.e., what did cognitive science have to offer education). This created a partnership between us and my colleague Wendy Newstetter, whom they would hire into the new department and who became the co-principal investigator on our NSF-funded research. Our NSF funding, in turn, led to our creating a research group for conducting investigations of the cognitive and learning practices in the labs. Creating what they called "a cognitively informed educational program" was a novel conception consonant with novel objectives.

If successful, it would put them on the map as leaders in education as well as research.[12]

Much cognitive science research has established that making students active participants in their learning is more effective than simply lecturing to them, and in the sciences, this holds particularly true when they are engaged in attempting to solve authentic problems.[13] In the K–12 area, there was by then a long history of learning initiatives based on *problem-based learning* (PBL) activities. We were thus predisposed to find a way to make PBL central to the developing curriculum. Our choice was further reinforced by the fact that the method is widely used in medical education as a means of preparing students for the clinic and thus familiar to the medical faculty. With medical PBL, small groups are presented with problems—rich and complex real-world medical cases—that enable them to engage in the authentic practices of the field, with "scaffolding" created by the teachers (who act as "facilitators" to student problem-solving) to support their developing expertise in diagnostic practices. In the course of problem-solving, they develop a deep understanding of the human body, diagnostic capabilities, and an identity as medical problem solvers. PBL, as used in medical schools, scaffolds the kind of hypothetical deductive and inductive reasoning needed for diagnosing ailments. We argued that the model-based reasoning (Nersessian et al. 2003; Nersessian 2008, 2009; Nersessian and Patton 2009) used in engineering problem-solving requires a different kind of scaffolding that needs to be developed with the faculty. To distinguish the practices, we called the new PBL-informed method for engineering education *problem-driven learning* (PDL). Over time, through several iterations, this method has been woven into the BME curriculum. At the graduate level, there are two core PDL classes, and at the undergraduate level, there are three core PDL courses, two classes, and one instructional lab, all created collaboratively with the faculty (Newstetter 2006; Newstetter et al. 2010). Notably, as the undergraduate level developed, it began to provide an additional pool of lab researchers. Much of the rest of the curriculum at both levels has evolved to contain significant PDL elements developed by individual faculty members who were inspired by their experiences as facilitators of the introductory PDL course (all faculty facilitate). Thus, PDL, as a method, has become generatively entrenched, providing structuring constraints for course design in this and other BME programs our curriculum has influenced.

The introductory course is taken by all incoming students, who work in groups of eight on the problem outside of class and with one faculty or postdoc facilitator during the class periods.[14] The problems tackled are carefully designed by the faculty to present complex, ill-structured health-care problems drawn from the real world, which encourage students to integrate and anchor their developing bioscience and engineering knowledge. For example, in a problem about cancer screening, student teams must formulate and address questions concerning the biology of cancer, current screening technologies (e.g., CT scans or MRI), and future screening strategies (e.g., at the nanoscale) and develop statistical models, among other topics. There is now a substantial repository of problems that faculty can draw from and modify to keep up to date.

It is important to underscore that the curriculum development was not a linear process. Hutchins has characterized learning as "adaptive reorganization in a complex system" (Hutchins 1995, 289). We (my research group) and the BME faculty were also learners, and much "adaptive reorganization" took place in the early years of this curriculum development. One important dimension was that prior to our reseach, scant research had been conducted on the cognitive practices of biomedical engineering (or any field of engineering). Further, although university research laboratories are the main training grounds for future researchers, they have rarely served as sites for studying situated learning. We proposed a program of "translational research" that focused on translating insights about the nature of cognitive practices and effective strategies for supporting learning and problem-solving in research labs into the instructional setting. A major goal was to infuse the curriculum development with insights drawn from studying the situated research practices of BME, such as those of Lab A briefly outlined in this chapter.

Our philosophical and cognitive science research objective was to illuminate the ways in which the social, cultural, material, and cognitive aspects of practice and learning are intertwined in the research setting. We analyzed the ecological features of the research labs—the cognitive, investigational, and interactive practices—that invite and support complex learning and used them to guide design principles for instructional settings. Our findings led us to characterize the research labs as *agentive learning environments,* where researcher–learners are made agents of their own learning, unlike traditional passive instruction via lecture and the canned, recipe-driven instructional lab. These findings reinforced our initial choice of PDL as a pedagogical method. Now, learning scientists and experienced faculty work with incoming faculty,[15] which, together with the repository of PDL problems, constitute a "faculty incubator" that provides cognitive-cultural saffolding for their rapid participation in what for them is usually a novel pedagogical method and learning-centered BME ecosystem. Finally, through the outreach efforts of our learning researchers, the BME faculty, and the PhD students of the program who have gone on to university appointments, significant elements of our PDL approach have become generatively entrenched in other BME programs in the United States and internationally.

THIS CHAPTER has provided a glimpse into the complex processes through which cognitive-cultural scaffolding for research is created in the process of the lab articulating itself as an evolving distributed cognitive-cultural system. Although I have looked only at the tissue-engineering lab here, the highlighted features of these processes transferred robustly across the other BME labs we studied. Designing, redesigning, building, and experimenting with hybrid physical models that simulate selected aspects of in vivo phenomena is a central practice of these communities. Simulation models are the signature technologies of a lab and provide the structuring constraints that afford ways of furthering the research program without rigidly specifying in advance what moves can be made. One model can provide possibilities for creating other models that can interlock with it in extended experimental model systems. A major reconfiguration took place shortly before we entered Lab A because of the researchers' felt need to have a better model of the blood vessel wall than could be provided by their practice of studying the reactions of "*cells in plastic to fluid flow.*" As we saw, the existing flow loop device facilitated and constrained the lab's development of the construct model, which in turn opened a range of new possibilities for research, including the creation of a novel animal model system and a line of stem cell research.

What this brief analysis establishes is that cognitive-cultural scaffolding becomes generatively entrenched in the evolving research program as "the lab" builds itself in the course of building the research technologies and the researchers. A highly significant part of the educational scaffolding directed toward creating hybrid researchers is the "repeated assembly" (Caporael 1996, 2014) of a PDL method through the years of the curriculum and of lab researchers who have at least the introductory PDL course in common. Further, the development of educational scaffolding for facilitating BME research provides a demonstration of "the manner in which epistemic integration interacts with organizations and institutions" (Gerson 2013, 515). Existing institutions adopted the notion that innovative research required a richer epistemic integration of BME, which in turn required the creation of new institutions and modes of organization, including a novel educational program, generatively entrenched in new kinds of buildings designed specifically to foster interdisciplinarity and a new kind of cross-university department aimed at creating hybrid researchers, themselves poised to work at the forefront of BME and to extend the frontiers for the next generation.

NOTES

I am grateful to the U.S. National Science Foundation for the funding required to carry out a project of this scope (REC0106733 and DRL0411825). I appreciate also the support of the Center for Philosophy of Science, University of Pittsburgh, where the final version of the chapter was written. I thank my fellow fellows, postdocs, and John Norton for their helpful comments on a draft discussed in our reading group. The chapter has also benefited from comments by participants during the "Beyond the Meme" workshop from which this volume derives. I thank the editors for inviting me to participate and for their comments on the penultimate draft, which significantly improved this article.

The research on which this analysis is based was a joint undertaking with my research group. I thank the members of the Cognition and Learning in Interdisciplinary Cultures (clic.gatech.edu) research group for their extensive and creative contributions to data collection, analysis, and interpretation; notably, for Lab A: Wendy Newstetter (co-PI), Elke Kurz-Milcke, Lisa Osbeck, Ellie Harmon, and Jim Davies. We are grateful to the lab director and researchers for welcoming us into their work space, granting us numerous interviews, and being so generous with time.

1. I use *cognitive-cultural* as an abbreviation for "cognitive, social, cultural, and material" dimensions as understood in science studies fields and for what Hutchins termed "socio-technical systems."

2. Gerson (2013) rightly cautions against the unreflective appropriation of biological metaphors for analyzing culture. However, Wimsatt (2013a) argues for the appropriateness of the ecosystem analogy for characterizing cultural evolution "because of the multiple evolving and interdependent lineages acting on different time and size scale" (564), which, as we will see, aptly characterizes the complexity of the evolution of the lab technologies, people, and practices as distributed cognitive-cultural systems.

3. See also Gerson (2013), Shore (1997), and Wimsatt (2013a).

4. All italicized quotes are taken from interviews with the researchers.

5. Carrying out this project required building our own interdisciplinary research group (with expertise in philosophy of science, history of science, anthropology, linguistics, psychology, artificial intelligence, human-centered computing, public policy, design, and qualitative methods) and developing innovative methods of data collection and analysis.

6. 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).

7. It is through fine-grained analysis of the processes of the coevolution of cognitive and cultural practices in science that we come to understand how, contra Kuhn, scientific change is continuous but not simply cumulative development (Nersessian 1984). Importantly, such analysis enables us to reveal the structuring constraints of prior conceptual structures and theories that contribute to the creation of genuinely novel concepts and theories (Nersessian 2008); see also chapter 4 of this volume.

8. Of the PhD students, three graduated while we were in the lab, and four graduated after we concluded formal data collection. We attended the dissertation defenses of the latter students and obtained their dissertations for our archive.

9. The notion of "interlocking models" we have developed is complex and cannot be developed fully within the confines of this chapter. Briefly, it is a multidimensional notion that serves to articulate relations among the components of the laboratory cast as a distributed cognitive-cultural system. Exemplars of interlocking models are physical models that interlock biology and engineering components, researcher mental models that interlock with artifact models in simulation processes, and configurations of models that interlock in experimental situations (Nersessian et al. 2003; Nersessian 2009; Nersessian and Patton 2009).

10. As a field, BME had been in existence since at least the early 1960s, but there were a few established departments, most notably at Johns Hopkins University (est. 1962). Since this is not a historical account of the field, I will present the situation as the founders of this new department expressed it to us.

11. Although I cannot articulate it in the confines of this chapter, there are significant insights to be gained regarding the explicit formation of interdisciplinary research fields—characteristic of much late twentieth- and early twenty-first-century science and engineering—by examining them

through the lens of research on “social movements” (see chapter 2). In the case at hand, the call of these researchers for a new breed of biomedical engineer suited for the twenty-first century came well in advance of an articulated means to carry out the objective, but it was a collective normative vision, the broad outlines of which were announced to the administrations of the schools involved, the wider intellectual community, funding agencies, and prospective donors. Importantly, it made a bid to reshape the knowledge-producing practices of a field, which the leaders felt needed to move beyond collaboration to hybridization in order to meet specified goals for twenty-first century BME.

12. Interestingly, they did not get the NSF engineering research center on that round but decided to proceed with what they dubbed “a cognitively informed” educational program anyway. The gamble paid off in that in approximately five years they went from nonexistent to the number two BME department in the *U.S. News and World Report* rankings, recently taking the number one spot over such rivals as the long-established Johns Hopkins department, the Massachusetts Institute of Technology, and Stanford. Twelve years after the program started, they won the state regents’ award for the best educational program in the state. The program has been awarded the 2019 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education by the National Academy of Engineering. These prestigious awards also provide validation for the “translational approach” pioneered in our research.

13. In cognitive science the notion that problem-solving is central to scientific thinking stems from the work of one of its founders, Herbert Simon, who traces his intellectual roots to the Würtzburg school of psychology, as does Karl Popper, for whom problem solving is the generator of scientific progress (Berkson and Wettersten 1984).

14. Because the BME-dedicated building was under construction as we began to plan the implementation of the PDL approach, five specially designed classrooms were constructed with seating and wall-to-ceiling whiteboards surrounding the room to facilitate interaction among the participants. Since we were doing research on the courses, two rooms were equipped with a separate observational window and recording compartment. The plan for students to work in groups of eight with a facilitator was recognized as costly from the outset, but the educational experiment is seen as so successful by the administration that it has continued to support the model despite significant growth in the student population. In recent years more than 160

undergraduate students are enrolled per semester, with facilitators needed for more than twenty teams, plus graduate courses.

15. The department has hired its own cognitive and learning scientists to provide support for ongoing curriculum development.

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