A Mixed-method Approach to Studying Distributed Cognition in Evolving Environments

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Abstract: In our study of a biomedical engineering laboratory, we construe the lab as adynamic distributed cognitive system evolving in time. We have foundthat a full understanding requires in-depth observation of the lab as it presently exists as well as research into the history of the lab and theexperimental devices used in it. To do this we use both ethnography andcognitive-historical analysis. The experimental devices in the distributed system have biographies of changes in response to problems over time. Learning requires coming to understand these aspects of devices. It occurs through mentorship and by discovering the locus of sources of knowledge distributed among the researchers within the interdiscpline of BME.

Keywords: Cognitive Science, distributed learning environments, science education, learning communities

1. Introduction

We are conducting a study of expert and novice researchers in biomedical engineering (BME) laboratories to develop an understanding of 1) the nature of reasoning and problem solving in this interdiscipline, 2) the kinds of representations, tools, forms of discourse, and activities utilized in BME work, 3) how these support practice, and 4) the nature of the learning challenges faced by novices as they are apprenticed to the work of the lab. To date we have been conducting both ethnographical studies of the day-to-day practices and cognitive-historical analyses of the problems, objects, and models employed in a tissue engineering laboratory (lab A). Although this is research-in-progress, we are finding the synergy between the methods has been invaluable to our developing understanding of practices and learning challenges in the lab, which we construe as dynamic distributed cognitive system evolving in time. Ethnographic studies tell us what BME practitioners do in the context of their research and cognitive-historical studies provide insight into how and why these cognitive practices have evolved.

2. A mixed-method approach

To date there has been little cognitive science research conducted on scientists and engineers in their work environments. Most of the research on the cognition of scientists and engineers has been "cognitive-historical" (Nersessian, 1995). Cognitive-historical analysis uses historical records to recover how the salient representational, methodological, and reasoning practices have been developed and used by practitioners in a domain, and interprets these in light of salient cognitive science investigations and results. These studies have focused largely on individuals, including Faraday (Gooding, 1990; Nersessian, 1984; Tweney, 1985), Maxwell (Nersessian, 1992, 2002), and Bell (Gorman & Carlson, 1990). The accounts are not historical narratives. Rather, the goal is to enrich understanding of cognition through examining the development of cognitive practices in science and engineering domains.

Cognitive-historical study involves the in-depth and fine-grained analysis of practices in various contexts and over time spans of varying length, reaching from shorter spans defined by the analyzed activity itself to time spans of historical dimension. The aim of the intersection of cognitive and historical analysis is to understand and interpret the practices in terms of cognitive categories. The existing literature in cognitive-historical analysis has tended to focus on concept formation, concept use, and conceptual change (See, e.g., (Gooding, 1990; Kurz, 1997; Nersessian, 1984, 1992; Tweney, 1985, 2002)). In the present study of BME reasoning and problem solving, the cognitive-historical analyses are focused on the objects that push BME research activity and are shaped and re-shaped by this activity. These objects come into being, change, and fall into oblivion, usually with a unique path of transformation in between. In lab A, we have identified devices that were newly developed and introduced to the field, and we have witnessed the use and development of new biological artifacts, such as stem cells and constructs emulating cardiovascular tissue. Other objects have disappeared from the activities in the laboratory, in particular, certain mammalian body parts, such as canine arteries. These and other objects become and remain part of the lab's biography. How the lab members appropriate this biography is subject to ethnographic analysis, which we have been carrying out.

In contrast to cognitive science, ethnographic and ethnomethodological studies of scientists and engineers at work abound (See, e.g.,(Bucciarelli, 1994; Latour & Woolgar, 1986; Lynch, 1985; Pickering, 1995; Traweek, 1988)). Such studies seek to understand science and engineering work as the participants understand it. This means uncovering their interpretive or meaning-making frameworks, the situated practices/activities, and the tools utilized in the environment that support both the work and the on-going meaning-making. Ethnographers aim to describe and interpret the relationships between scientific practices and the social, cultural, and material contexts where they occur. The material media employed in working in laboratories has been of particular interest. Objects as simple as paper and blackboards, and as complex as computer generated graphs have been identified as supporting and sustaining the intellectual activities in science labs. Studies of these forms of support illustrate how the material aspect of the work environment impacts the meanings that can be possible and the understanding that can follow as a result.

Ethnographic studies of situated cognitive practices have been carried out on everyday cognition in learning situations and in the workplace. These investigations have focused on the roles the environment or context plays in problem-solving. For example, in a study of "outdoor" mathematics or math in everyday settings, Lave illustrated how contextual artifacts such as countertops and measuring cups are critical to problem-solving in real-world settings (Lave, 1988). Likewise, Hutchins (Hutchins, 1995), demonstrated in his study of navigation on board a Navy vessel how cognition is located not just in the head of one individual, but rather within a complex, *distributed* system of people, representations, and machines. These ethnographic studies of everyday cognition in work and home settings forcefully present the need to understand cognition and context in relation to one another. Clearly the same need exists for the case of cognitive practices in scientific and engineering contexts. Recently cognitive researchers have begun to carry out ethnographic studies of these practices (Dunbar 1995; Goodwin, 1995; Hall et. al in press; Ochs & Jacoby, 1997), but these studies lack the biographical dimension that we find important to our study.

3. Case study: A tissue engineering laboratory

Lab A applies engineering principles and methods to the study of living cells and tissues for the eventual development of artificial blood vessels. The lab members all come from a predominantly engineering background. Biological knowledge is embedded in the artifacts they construct and in the model-based reasoning they employ in the course of research. An *in vivo/in vitro* division provides a significant part of the cognitive framework guiding practice in the lab. The BME researchers use *in vitro* models or what they call "playing on the bench top" to screen and control specific elements they want to examine. For instance, one cannot try out various kinds of scaffolding in *in vivo* environments. A major research goal is to optimize *in vitro* models so as to move closer and closer to *in vivo* situations. When used as systems for the human body, the biological substitutes must replicate the functions of the tissues 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 that are embedded in the scaffolding material must replicate the capabilities and behaviors of native cells so that the higher level tissue functions can be achieved. Moreover, the type of cells identified for embedding in the substitutes must readily be available and compatible with adjacent tissues. This requires a method for ensuring cell growth, proliferation, and production.

Because the test bed or environment for these activities cannot be the human body, biomedical engineers have to design facsimiles of that environment where the necessary experiments can occur at each of the levels identified. These technological facsimiles, which in Section 4 we discuss as *devices*, are locally constructed *in vitro* sites of experimentation. A device is designed to achieve a goal, such as stimulating, proliferating or conditioning. The researchers in the lab call the process of constructing and manipulating *in vitro* sites "putting a thought into the bench top and seeing whether it works or not." These instantiated "thoughts" allow simulations of a controlled *in vivo* context, such as the knee or the artery, that are constructed to approximate the local forces at work. The "bench top", as one researcher explained, is not the flat table surface, but comprises all the locals where experimentation takes place.

4. The BME lab as an evolving distributed cognitive system

The laboratory, as we construe it, is not simply a physical space existing at the current time, but rather a *problem space* defined by the research program of the senior scientist, who directs a group of younger scientists and students, that is reconfiguring itself almost continuously as the research program is moving along and taking new directions in response to what occurs both in the lab and in the wider community of which this research is a part. Construed in this way, the notion of 'problem space' takes on an expanded, richer meaning than is currently employed by the predominant cognitive science characterization of problem solving as "search through a problem space." Here the problem space comprises models and artifacts together with a repertoire of activities in which simulative model-based reasoning assumes a central place (Nersessian, 1999).

We find the best way to characterize the reasoning and problem solving in this lab is as *distributed* and *situated*. We are looking at the *cognitive systems* comprising one or more researcher and the *cognitive artifacts* involved in a problem-solving episode; where 'cognitive systems' are understood to be "socio-technical" in nature (Hutchins 1995) and 'cognitive artifacts' are material media possessing the cognitive properties of being, generating, or manipulating representations. On this model, which for simplicity here we will refer to as 'distributed cognition', the cognition "refers not only to universal patterns of information that transpire inside individuals but also to transformations, the forms and functions of which are shared among individuals, social institutions, and historically accumulated artifacts (tools and concepts)" ((Resnick, Levine, & Teasley, 1991). See also, (Giere, 2002; Greeno, 1989a; Hutchins, 1995)). We are using a distributed cognition model to understand the nature of the representations in the system and the processes that operate on these in the knowledge-making activities in the lab. However, we find in thinking about cognition as it functions in this lab that none of the current conceptions of distributed cognition in the literature are adequate in that they fail to provide for systems that are evolving in time.

In studies of cognition in work environments, for instance, the cockpit or on board a ship, it is often the case that the situations change in time. The problems faced by a pilot change as she is in the process of landing a plane or bringing a ship into the harbor, but the nature of the technology and knowledge of the crew are relatively stable. The cognitive system is dynamic yet largely *synchronic*. To understand cognition in the BME laboratory requires seeing that the situation is dynamic and *diachronic*. This cognitive system undergoes progressive change. The technology and researchers have evolutionary trajectories that must be factored into the understanding of the cognition at any point in time. BME researchers, assistants, and students have biographies that become part of the lab history; as do the multiple and diverse objects that are manipulated and transformed in the lab. For example, the researchers are mostly Ph.D. students who have learning trajectories; these, in turn, intersect with the developmental trajectories of the technological resources within the lab. In order to begin research, a student must first master the relevant aspects of the biography of an artifact necessary to the research and then figure ways to alter it to carry out her new research project when the new research problems demand. One highly significant artifact in the lab is the *flow loop*, a device that emulates the shear stresses experienced by endothelial cells within blood vessels. A Ph.D. student we interviewed discussed how the researcher prior to her had modified the flow block part of the loop by making it into one piece rather than several because the multiple pieces had allowed leaks and caused more cell contamination with bacteria – a constant problem in this line of research. The previous research had been conducted on smooth muscle cells. The new student was going to use the flow loop to experiment with vascular constructs that are thicker than the muscle cells, and are not flat. To begin that research she, together with another new student, had to re-engineer the flow loop by changing the width of the flow slit that holds the spacers. Because the cells are not flat, spacers need to be used between the block and glass slide parts of the loop in order to improve the flow pattern around the boundary to bring it more in accord with the human model.

We find the mixed methodology approach essential to our analysis of cognition and learning in this kind of environment. Cognitive-historical analysis allows us to tell the biographies of the components of the cognitive system on multiple levels, including their physical shaping and re-shaping in response to problems, their changing contribution to the models that are developed in the lab at any particular time, and the concepts that dominate the research activity. Studying the nature and function of the technology in the laboratory includes their distribution within the lab, the organization of workspace, and the social organization of the lab. For instance, the *hood*, which is the sterile work bench, is where cells meet devices. But it is also a major site for learning and didactic interaction, especially between mentor and mentee. Observational study allows us to obtain traces of these transient arrangements that ground the BME research activity in active manipulation of objects, laboratory routines, and the social organization of the lab.

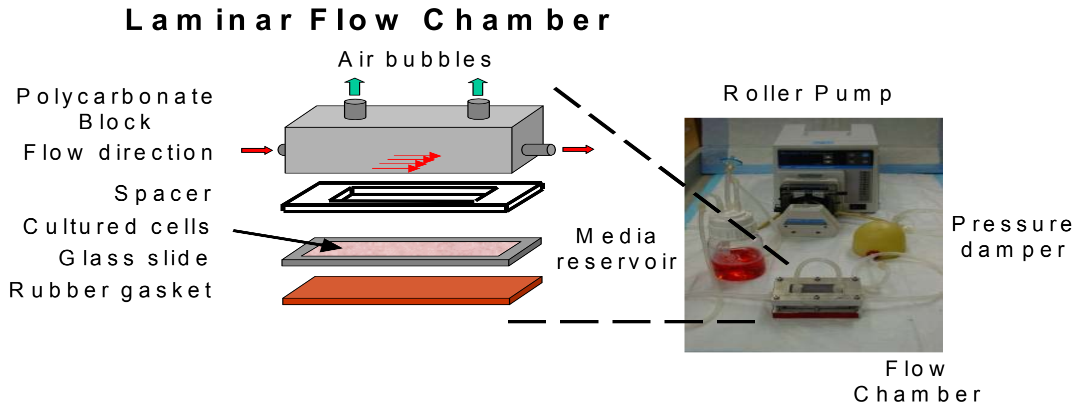

Figure 1: Diagram and photograph of a flow loop

The issues of agency and intention within a given cognitive system, especially in a situation where experimentation and instrumentation are intrinsic to knowledge-making, is a pressing question for cognitive science research, both in the development of the theoretical foundations of cognitive theory and in relationship to learning in science and engineering. To better understand these issues, our developing approach to evolving distributed cognition as it functions in lab A has focused on the material media employed in experimentation. We have identified devices that were newly developed and introduced to the field, such as the flow loop; we have observed the use and development of new biological artifacts, such as stem cells and constructs emulating cardiovascular tissue; we have examined the role of information technology. We have developed a tentative classification of the various material media ranging from devices (engineered facsimiles that serve as *in vitro* models), to instruments (generate measured output), to equipment (assists with manual or mental labor). Developing categories of these material media and determining their relationships to representations and cognitive processes in the lab promises to further refine recent reflections on forms of cognitive functioning that are less bound to abstract representational systems or individual minds.

The cognitive artifacts in the distributed systems in the lab cut across these distinctions, though most are instruments or devices. We have been focusing on the devices because these are the material media the lab researchers create and modify in their work and because they embed biological knowledge. Part of the biography of a device involves gaining new independent variables, such as changing the flow loop to have pulsatile flow where before flow type was not manipulated. Within the cognitive system of the lab, devices instantiate part of the current mental model of the phenomena and allow simulation and manipulation. In this context, we understand a *mental model* to comprise both what are customarily held to be the *internal* thought of the human agent and the *external* device. Understood in this way, simulating the mental model involves the processing of information both in memory and in the environment (See, (Greeno, 1989b) for a similar view). The intent of the simulations is to create new situations that parallel *in vivo* situations.

Devices, such as the flow loop and the *bioreactor*, a device that enables the researcher to compare the vascular construct in conditions of static fluid flow (*in vitro*) with the pulsed fluid flow experienced by cells in arteries (*in vivo*), are constructed and modified in the course of research with respect to problems encountered and changes in understanding. These devices have a history within the research of the lab. For example, the flow loop was first created in this particular lab and the bioreactor, though having a longer and more varied history, was not used before for the purpose this lab employs it. We have been studying the history of the past *generations* of these devices and observing how they are functioning in the contemporary situation. In an interview with a Ph.D. student in his second semester in the lab and now considered the “resident expert” on the bioreactor, he discussed some of its recent history:

I(interviewer): Do you sometimes go back and make modifications? Does that mean you have some generations of this?
A 10 : Uh yes I do. The first generation and the second generation or an offshoot I guess of the first generation. Well the first one I made was to do mechanical loading and profusion. And then we realized that profusion was a much more intricate problem than we had - or interesting thing to look at - than we had guessed. And so we decided okay we will make a bioreactor that just does profusion on a smaller scale, doesn't take up much space, can be used more easily, can have a larger number of replicates, and so I came up with this idea.

He continued by pulling down the various generations of bioreactor and explaining the modifications and problems for which design changes were made.

Over time, as a device is iteratively redesigned and used by different researchers, it becomes "black-boxed". Its historical evolution in response to immediate problems disappears. Newcomers to the lab, who are seeking to find their place in the evolving system, encounter these devices as materially circumscribed objects. Growing cognitive membership in the lab involves a gradual process of coming to understand these objects as devices - as objects with evolving trajectories, constructed and employed to respond to problems, to help answer questions, and to generate new ones. A vignette of a relatively new Ph.D. student we have constructed from observations, interviews, and a research presentation at a lab meeting will serve to illustrate this point.

Melissa (pseudonym), a graduate student with an undergraduate degree in mechanical engineering, who joined the lab only a couple of months ago, is struggling. In a research meeting she cannot hide her frustration. Currently, she is heavily involved in cell culturing activities. Encouraged by the PI, she articulates a number of problems and questions, most are concerned with the biological aspects of her project. She needs to know how to quantify a certain protein. Standard procedures exist but she is not familiar with them. Her project involves culturing cells for 60 days or longer. What kinds of additives in the media should she use for long-term culturing? She wants to protect her cultures from contamination, should she change the media less frequently, or even not at all? Since she is culturing three different types of cells which, as she has found out already, grow at very different rates, how can she "speed up" cell growth with some of her cells? These issues result in a lively exchange of suggestions, experiences, and new questions during the lab meeting.

From observations in the lab and interviews with Melissa, we know that cell culturing *per se* was not the only source of frustration for her. One of the mechanical devices had also caused her major anguish: The constructs in her bioreactor kept leaking. One use of the bioreactor in lab A, is as a device that exposes cells seeded on silicon sleeves to pulsatory flow. This procedure is also known as "preconditioning" the cells while they grow into a confluent structure. Preconditioning has been shown to improve the mechanical properties of tissue-engineered blood vessel constructs. For Melissa, preconditioning means to "exercise" the cells. Sitting at the hood, Melissa uses tweezers, one in each hand, to mount 1 1/2" long silicon sleeves that have been seeded with cells on the bolts in her bioreactor, Her task is to slip each sleeve over two bolts on opposites sides of the main reservoir of the bioreactor, which appears similar to an open rectangular box with two sets of four horizontal bolts at opposite walls of the box.. The reservoir is filled with media and media is also pumped through a closed tubular circuitry, including to the bolts and sleeves. A site that is particularly prone to leakage from this circuitry into the main reservoir is where the sleeves are mounted on the bolts. Melissa can often tell that there is leakage by simply looking into the main reservoir of the bioreactor while it is operating. When she sees ripples in the fluid media close to the bolts, she knows. This has happened many times. At best, she was able to get two of four sleeves to operate leakage-free for two days, where she needs four for four days.

Melissa practiced mounting sleeves on bolts and instead of one suture to fix the sleeve more tightly to the bolt she used two. Still there was leakage. She practiced mounting and investigated the reason for the leakages, eventually using water and mere silicon sleeves. Then she learned that another lab member, Jason, had run into similar problems, having many leakages with his bioreactor, but only when he used the new silicon tube, the one that Melissa had used for her experiments. Melissa has not worked with the bioreactor in the last couple of weeks. She has mostly done cell culturing but will have to return to the bioreactor soon. She says that the possibility that the problem it is not simply her but potentially related to the material made her feel a little better, but she had to get away from this task for a while. Meanwhile she is closely observing the progress that Jason, currently the lab's wizard on the bioreactor, makes with preventing leakages. Jason has developed an alternative to the metal bolts; his bolts are made of plastic and are arrow-like in shape. Melissa is beginning to have her own ideas about how to improve this aspect of the bioreactor. She is thinking of having a second grove carved into the metal bolts to better fixate the second suture that she started using to fixate the sleeves. She might also use clamps to fixate the sleeves. If Jason's system works out well, she might go with that, but otherwise will go back to her "clamp idea."

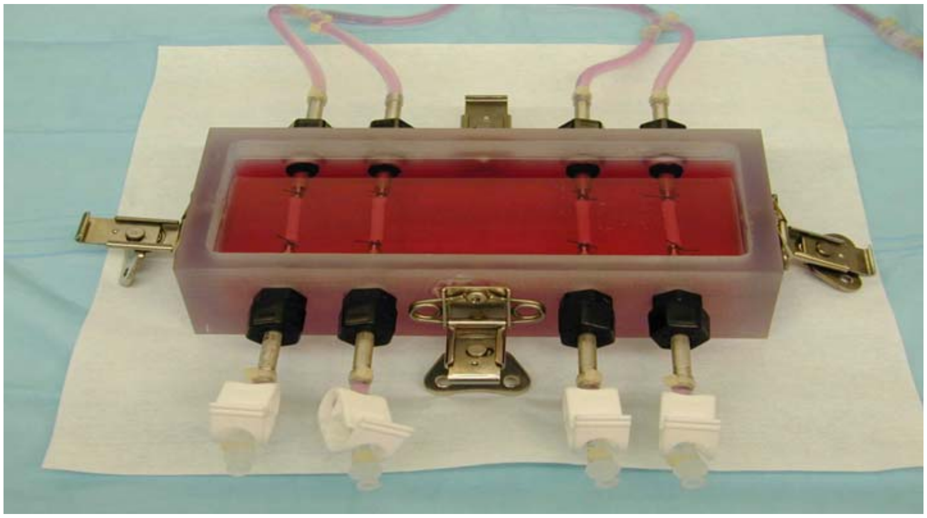

Figure 2: Photograph of a bioreactor

5. Learning challenges in an evolving distributed cognitive system

Undergraduates and graduates new to the BME laboratory encounter numerous learning challenges. In a real sense, they are foreigners attempting to act in an unfamiliar culture. Upon entering the lab for the first time, they see bench tops covered with a jumble of glass and plastic equipment. They notice many kinds of machines and objects piled on shelves and on the bench top. They see several rooms that seem to have varied functions. Some doors are closed; others are open. They experience this world as existing only in one slice of time. They hear language that is foreign; words that they cannot really make out and certainly do not understand. They observe detailed, methodical procedures that seem relatively easy, but when attempted are fraught with hidden stumbling blocks and even smaller unarticulated steps. For instance, the *mechanical tester* is a device used to test the strength of the vascular constructs. One new undergraduate research student discussed it in the following way.

I: You are an ME (mechanical engineer). Have you used any ME?
A 2 : Not yet. I am starting tomorrow to do mechanical testing on some constructs I have made so I know I will use some of it then, but that will be the first time.
I: How will you do that?
A 2: I'm not sure yet. A 7 (experienced grad student) is going to do it with me tomorrow and so - just watch her at the beginning.
I: So you're not sure how it's going to happen?
A 2: No. I've seen the machine and I saw her calibrate it and set it up so that it is ready to go but I know that we are pulling little slices of the construct – they are round, we are just pulling them. It's the machine that is right there before the computer in the lab. The one that has the big "DO NOT TOUCH" on it
I: Is it an axial strain (mechanical tester)?
A 2: I know it has a hook on it and pulls.

Clearly, the complexity of the work being supported by the distributed cognitive system can easily overwhelm the learner.

Engineering students initially experience a cultural shock as they learn to participate in the biology-based lab. The first order of business is to learn to grow and culture cells because this is the starting point for just about any work in the lab. But this first critical activity is alien on many levels to engineers. They have to master minute steps with precise kinds of equipment - the sterile hood, the incubator, the centrifuge - and equally fine motor movements. It is easy to make a little slip of the hand, which will contaminate the cells. Knowledge about how to participate in this lab, knowledge about the biology aspects and the engineering aspects, and knowledge about the research questions under study and their evolution resides in various locales. Information on culturing cells can be found in notebooks that describe the protocols. These are helpful, but not sufficient for actually doing the work. The finer actions, the minutiae of avoiding contamination, have to be demonstrated and taught by senior lab members.

Learners new to the system need to know when to ask for help and whom to ask. Each graduate student and postdoc is a potential repository of knowledge. Some have procedural knowledge on specific lab techniques, some become local experts on a device and are indispensable when things go awry. Some have spent time in the basement with the histologist from whom they have learned the subtleties of reading stains and slides. The most senior lab members may be able to articulate the research trajectory such that the current work is situated in prior concerns, questions, and tools. A major learning challenge is knowing where in the system the needed knowledge resides.

In apprenticing to the work of the lab, the learning steps and decisions are constrained by the types of devices, instruments, and equipment that come on board as the learner moves forward in the research activities. The challenge in this type of action-centered, methodology learning is that the steps being taken are not well grounded in the higher level goals of the research in the lab. The undergraduate learners are very adept after 3 months in explaining "how" they do their work. They are much less able to explain "why" this work is important, where it fits in other types of activity, and how it helps to drive forward a larger agenda.

New researchers are often expected to pick up and carry on with a path of work initiated by a former and soon-to-graduate student. It is common for the tools of that line of research to be passed on to these new Ph.D. students. In one case, a bioreactor had been passed on to a student we interviewed who had been in the lab only four months ("Melissa" of the vignette above, now in the lab ten months). In asking her, at that time, to explain how this bioreactor worked and how it fit into the research the lab was undertaking, we found she had experienced several learning challenges. Of primary importance was the problem of the device itself. How does it work? How do the parts fit together? What can it do? Of particular interest to us was her observation that she "had trouble relating to the way he [prior "expert" student] used to work with it." This reflection underscores for us the importance of the biographical dimension of each of the devices in the lab. Relatively new lab members do not yet have access to the knowledge that is embedded in the devices. For them these devices are detached from the knowledge-making processes and their goal is to master these only technically, such as taking them apart and putting them back together.

6. Summary

Bringing biographies of scientific objects to life and making sense of the day to day activity in a BME lab are prima facie separate tasks. We experience, however, that the research process in this distributed cognitive system evolves at a fast pace, which necessitates going back and forth between the two endeavors. The ethnographic study of the development, understanding, and use of particular devices by various lab members, as well as ethnographic interviews have allowed us to conjoin the cognitive-historical study of biographies of lab members, lab objects, and the lab itself with an eye on the perception of these entities by the lab members themselves. With relatively new lab members, undergraduates, and new Ph.D. students, especially, the sparseness of their biographical knowledge of BME objects is an obstacle to their learning and integration into the cognitive system. Without such knowledge they are confronted with bio-engineering devices in the lab that for them remain detached and lifeless entities that they attempt to master only technically.

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