Cognitive Partnerships on the Bench Tops

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Abstract: Research laboratories or what we are calling innovation communities, are potentially rich sites for understanding situated learning since their goal is to develop new knowledge and innovative practices. Here we report on a two year study of learning in a tissue engineering lab, an evolving community of practice in the historically recent field of biomedical engineering. Findings suggest the critical role artifacts play beyond merely being part of a distributed cognitive system. Lab artifacts such as cells and engineered bio-substitutes offer potential *cognitive partnerships* to learners. Over time, understandings are constructed, revised, enhanced and transformed by learning *through* and *with* the artifacts present in the community. We find that these dynamic relationships are critical to knowledge acquisition and deepening forms of participation and in their developed stage, best described as partnerships which support model-based and simulative reasoning.

Introduction

We are studying research laboratories as part of a larger project aimed at designing optimal learning environments for students in the field of biomedical engineering. This relatively new sub-field of engineering is an instance of what we term an *interdiscipline*. We use this term to denote an interdisciplinary area that has evolved in such a way that the melding of knowledge and practices from more than one discipline spawns highly unique environments and innovative practices, both cognitive and material. In the case of biomedical engineering, meldings of quantitative/qualitative/descriptive methods and varied forms of model-based reasoning from biology and engineering work together to create new ways of thinking and working towards designing and building medical applications. At present there are almost no textbooks for undergraduate education even though the number of new BME degree programs swells every year. More importantly, however, is the challenge of creating learning environments that immerse students in truly interdisciplinary contexts. Our efforts to achieve this have been informed by two streams in the learning sciences community—problem-based learning and model-based reasoning. Very specifically, we are seeking ways to modify the PBL environment for engineering education in such a way that models come to the fore in problem-solving. With that goal in mind, we have been investigating BME research laboratories as exemplars of real-world problem-based learning contexts which utilize multiple forms of representation and types of modeling to push the frontiers of science.

Research laboratories, for some decades now, have been sites for ethnographic study of science and engineering practices (e.g, Bucciarelli 1994, Latour & Woolgar, 1986, Lynch, 1985) and also of observational (Dunbar 1995) and ethnographic studies of cognition (See e.g., Hall *et al*., in press; Ochs & Jacoby 1997), but rarely for investigating situated learning (e.g., Goodwin 1995). However, research laboratories, or what we term *innovation communities*, are specifically predicated on developing new knowledge and innovative practices suggesting the critical importance of both individual and communal learning. Such sites therefore have the potential for offering insights into features of rich learning environments. With an eye towards identifying and understanding those features, we have been investigating two laboratories working at the frontiers of science. Here we report on findings from one of these labs, findings we believe have important implications for science and engineering classrooms.

Laboratory A, a research community we have been studying for two years, is working to develop cardiovascular bio-substitutes. Ultimately, such vascular tissues will be built from the cell up and be readily available to patients suffering from heart disease. Since most of the knowledge needed to engineer human tissue has yet to be discovered, this lab is building the knowledge base required to take first fledgling steps in that direction. Such knowledge development entails experimentation, trial and error, failure and, above all, learning. In fact, you might say the major enterprise of this lab is learning, which makes it a rich site for investigating how environment mediates such activity.

Cognitive Partnering in the Lab

In trying to understand the role of environment and community, we follow up on Lave and Wenger's proposal for a "*decentering* of common notions of mastery and pedagogy" (Lave & Wenger, 1991) p. 94). Decentering for us means searching for mastery in varied forms and pedagogy as enacted through participation in situated activities and interactions. The particular argument we advance here is that participation as the vehicle for learning extends to interactions not just with people but *just as importantly with artifacts*. This argument relates to Lave and Wenger's notion of both " absorbing and being absorbed in—'the culture of practice' "(p.95). We have observed that artifacts are critical to this process of being absorbed into the practices. It is our contention that research laboratories as instances of innovation communities are not well understood unless we consider learning as relational with respect to people, communities, *and* artifacts. We further contend that our understanding of such communities can extend the current notion of distributed cognitive systems as it relates to learning (Hutchins, 1996). We find that artifacts as part of the cognitive system in such communities afford evolving *cognitive partnerships*. Such partnerships are special relationships formed with certain artifacts that are salient to the lab research agenda. These relationships are interesting in that they are both negotiable and changing through repeated and varied interactions. One artifact that seems to be singled out as a partner for all newcomers is the cell culture. Other potential partners might be what the lab members term "devices", which are lab designed and constructed artifacts that model real-world behaviors.

Our notion of a cognitive partnership offers alternative understandings of agency and intention, representational possibilities, and reciprocal relationships. Over time, learner understandings are constructed, revised, enhanced and transformed by learning *through* and *with* the artifacts present in the community. We have discerned developmental patterns enacted as changed understandings and uses of the artifacts both materially and cognitively. These dynamic relationships are critical to knowledge acquisition and deepening forms of participation. And of central importance to these cognitive relationships is their evolving nature (Nersessian et al., 2002). Significantly, innovation in technology and lab practices occurs continually, as does learning, development, and change in lab researchers. We find that very often innovation is carried forward through the evolution of the lab artifacts themselves. Thus, we characterize the labs under study as "evolving distributed cognitive systems". None of the conceptions of distributed cognition in the current literature account for systems that have an evolving nature. In Hutchins's studies of distributed cognition in work environments, for instance, the cockpit of an airplane or on board a ship, the problem solving situations change in time. The problems faced, for example, by the pilot, change as she is in the process of landing the plane or bringing a ship into the harbor. However, the nature of the technology and the knowledge the pilot and crew bring to bear in those processes are by-and-large stable. Even though the technological artifacts have a history within the field of navigation, such as Hutchins documents for the instruments aboard a ship, these do not change in the day-to-day problem solving processes on board. Thus, these kinds of cognitive systems are dynamic but largely *synchronic*. In contrast, we are studying learning in innovative, creative settings, where artifacts, and understandings are undergoing change over time. The cognitive and the learning systems of the BME research laboratory are, thus, dynamic and *diachronic*. Although there are loci of stability, during problem solving processes the components of the systems undergo development and change over time. The technology and the researchers have evolving, *relational* trajectories that must be factored into understanding the learning system at any point in time.

To better capture these evolving systems, we have been conducting both cognitive-historical analyses of the problems, objects, and models employed in the research and ethnographic analyses of the day-to-day practices in the lab. The ethnographic analysis uncovers the situated activities, tools, and interpretive frameworks utilized in an environment that support the work and the on-going meaning-making of a community. Cognitive-historical analysis uses the customary range of historical records to recover how the representational, methodological, and reasoning practices have been developed and used by practitioners in a domain over time. The practices are examined over time spans of varying length, ranging from shorter spans defined by the activity itself to spans of decades or more. In our study of BME practices thus far, the cognitive-historical analyses are focused on the technological artifacts that push BME research activity and are shaped and re-shaped by that activity. These artifacts become and remain part of the lab' history. How the members of the lab appropriate the history and employ the artifacts in their daily research is again subject to ethnographic analysis.

Innovation Communities and Learning

To understand the centrality of lab artifacts is to understand the nature of the work done in biomedical laboratories. Intimations of these cognitive partnerships are best illustrated through a scene in lab A, a tissue engineering laboratory, reconstructed from laboratory field notes.

The incubator room is more crowded than usual. A14, the laboratory manager, sits at one of the hoods working intently on muscle tissue extracted from a pig. He is trying to scrape off cells to be used in A7 experiment. A7, a third year Ph.D. student, trying to learn this technique, is seated right next to him watching intently while A22, a Masters student new to the lab, leans close to do the same. As he works, the lab manager discusses the problems of working with tissue. A5, another third year Ph.D. student, working in the facing hood, no more than six inches away, offers a suggestion. She too is removing cells from a "tissue", but this one is engineered, a biosubstitute created in the lab from a collagen matrix to which cells adhere. Back to back with the lab manager, she notes that it feels like "backseat driving." A5 explains to the observer that she is "getting the cells off her construct". The lab manager observes that he is basically doing the same thing, but A5 quickly retorts that her cells are "nicely lying straight" on her construct not on "some squishy mushy tissue". This allows her to use a brush for scraping off the cells, a technique that A7 has not seen. "You can learn a lot from watching other people", A7 observes. In the meantime, the Masters student, the lab newcomer, has been listening and observing all that goes on across these hoods. She assists by putting the cells A7 removed in the centrifuge but not before asking what speed and length of time to set the machine. The lab manager answers with a speed, noting that high speeds can kill the cells.

Back to back, the two Ph.D. students, A7 and A5 are working with cells as the building blocks of vascular tissue. A7's porcine cells come from the *in vivo* world of animals. In contrast or perhaps as compliment, A5's endothelial cells represent the *in vitro* world of the engineered model, which is evolving and very much under construction. The cells and the sites of these cells--the pig artery and the engineered vascular construct-- are not just materials that get worked on in the lab. Rather as we will elaborate they are critical partners in the quest for innovation, particularly the cells and the construct. This tight physical proximity of people in the environment embodies the closeness of the two focal research areas: the tissue engineering of cardiovascular substitutes and the development of better laboratory models for studying vascular biology. What is critical for learners to understand in this environment is the interplay between these two worlds. Cells from slaughterhouse specimens are removed and studied while cells form the "hothouse" specimen--the construct--are removed and studied as well. Two different worlds are enacted as parallel in this moment under the hoods as the engineered artifact is treated in the same way as living tissue. The mutuality and complimentarity of these two experimental worlds is played out repeatedly as knowledge evolves and disperses across members, newly identified research questions, decisions to purchase new equipment and design new devices.

Although lab members generally describe their work as "biological", their training upon entering the lab was primarily as engineers. Thus, commonly at the start of their apprenticeships, members identify themselves as chemical or mechanical engineers, but as they progress in their work, this self-description often changes to bioengineer or, in one case, it has even changed to "*bio-bioengineer*". Such transformed assignations powerfully suggest that affiliations and identities evolve for the individual and even the community as a whole in conjunction with evolving forms of participation. Lab learners cross disciplinary boundaries in order to appropriate and evolve new forms of reasoning and representation. Over time, once solitary learning journeys and discoveries capitulate into generalized lab practices. Put another way, individual biographies in the lab, or what we construe as the relationships between the 'players' in the environment, become a part of the lab's research history.

Innovation is driven by advances in both arenas and the interdisciplinary environment is where synergy is created. However, the laboratory, as we construe it, is not simply a physical space existing in the present. Rather it is a *problem space* that, in this case, is emerging with the development of an interdiscipline like BME. Disciplinary boundaries erode, old problem spaces shift in interesting ways, de-centering and re-centering, as innovation communities take form. New problem spaces arise that are constrained by the lab director's research program and reconfigured almost continually as the research program moves along and takes new directions in response to what occurs both in the lab and in the wider community of which the research is a part. Thus the space has permeable boundaries. It comprises people, technology, techniques, problems, artifacts and relationships. Overall Lab A is a site for the melding of knowledge and practices from biology and engineering. We see that very starkly in the scene described above where the biological tissue is worked on concurrently with the engineered tissue. Construed in this way, the notion of 'problem space' takes on an expanded meaning from that customarily employed by the predominant cognitive science characterization of problem solving as search through an internally represented problem space. In our characterization, 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). The lab problem space evolves through varied types of partnerships: 1) between biology and engineering, 2) between the different people with varied types of knowledge, and 3) between complimentary research questions under investigation 4) and between artifacts and researchers. Through these developing partnerships new individual and communal cognitive and cultural practices are forged as are new identities for the learners unfolding through changing roles, capabilities and understandings. Given this characterization of problem space as observed in the lab, what are the learning implications?

Cell Cultures as Objects, Cells as Agents

Of particular interest to us is the partnership between newcomers and the artifacts that populate and animate the lab space. For this paper, we have chosen to present our case around two kinds of artifacts ever present in the life of Lab A: cells and 'constructs', which is the lab term for the biosubstitutes under construction. Each provides a venue for cognitive partnering with implications for the development of knowledge, individually and communally.

Because cells are the building blocks of engineered tissue, it is no wonder that a senior graduate student stated that learning to culture cells is "*baseline to everything*". But understanding cells' needs, processes, reactions and possibilities is something that unfolds over time. More immediately, cell-culturing techniques are what a novice first learns in the lab. The gross steps are written down and kept in a protocol book but in reality they are learned through classically embodied apprenticeship practices. A senior graduate student works intimately with the new lab member in a series of dyadic exchanges that extend over numerous sessions. Intimate because the intricacies of culturing can only be observed at very close range--the mentor sitting with arms extended under the sterile hood, the newcomer hovering directly behind and over the shoulder of the cell manipulator, inches apart.

It is this embodied physical intimacy that begins to operate as a metaphor for the cognitive intimacy the novice researcher develops over time with the cells. This intimacy unfolds as the cells come to support the learner in generating, manipulating and propagating representations that change over time. Cognitive intimacy also develops with respect to issues of agency and intention. The cell as a kind of agent 'helps' the researcher in her intent to perform a simulation in order to create new situations, which parallel potential *in vivo* phenomena. Thus the cells act as a cognitive partner in knowledge building. But this intimacy takes a while to develop. Novices characterize first cell encounters as "*complicated*" because "*you have to focus on the moment*" and you have to "*think about things you can't see*." As engineers too, they have learned to grapple with things they cannot see--quantitative models of processes in thermodynamics as an example. But Lab A invisibility and the recalcitrance of the biological side of things is different from the challenges faced by engineers. Errors can ruin an experiment and cost several weeks of work. While not seeing in engineering work is costly over time, not 'seeing' in this environment is immediately damaging--a first lesson with the cells as potential partners.

We have observed that evolving cognitive partnership with cells has three stages manifest in contrasting notions of representation and agency. In stage one, the lab newcomer who is an engineer by training, experiences the cell culture as a detached object, which can be manipulated in various ways. They can be moved, fed, looked at under microscopes and counted, split or frozen. Learning at this stage focuses on those actions that are done to the culture. A graduate student was overheard telling a newcomer*: "Think of them as children or pets*." In using these terms, the senior student alludes to a slightly more involved understanding of the cultures. As time passes, and, this can happen very quickly, things happen to the cultures that begin to suggest that cells are agents, as are children and pets. Often, this quality seems to work to the detriment of the learner. Cultures die; they *"go bad*". They ruin experiments and require long weekends of "*babysitting*". They are now seen as objects with specialized needs, which require actions and behaviors on the part of the learner. This new model of the culture now entails both cells as objects that are acted on, but also reacting (often negatively) to environmental conditions. Interestingly, the director of another tissue engineering laboratory in the building said it was not uncommon for learners to "*get stuck*" in this stage. But to really move forward in their research, students had to move beyond this understanding of the cell culture to a different, more involved model of the cell-in-culture itself.

The third stage of learning we have witnessed articulates a relationship with cells that is best articulated as a partnership. We see this with the more advanced lab members and with other senior researchers in the building also doing cell-based work. Compelling evidence for this partnership can be found in the verbs used to describe activity attributed to cells. The following is an instance from an interview with a lab member: *"Um well, the cells once they are in the construct will reorganize it and secrete new matrix and kind of remodel the matrix into what they think is most appropriate."* Similarly, we offer a quote from a lab meeting where in a discussion one of the lab members said*:"I am not sure that the endothelial cells like that hybrid [She is referring to a particular kind of construct.]…It is also important that the endothelial cells see their neighbors, smooth muscle cells."* This and the previous quote were from researchers at the level of advanced graduate students. Reflecting this advanced understanding of cells as agents, an established researcher in biomedical engineering at a plenary address we attended responded to a question from the audience with: *"Cells make a lot of decisions with whom they want to connect with."*

In this new stage, learners come to see the cells as potential partners – that is, as playing a active role - in the research process. This new understanding of the cells as rich systems implies the potential for a working relationship. The cells can now do things with and for the researcher. One thing the cells can do is signal. They can also express. They can align, elongate and proliferate. With this new found appreciation for the richness of cellular systems, the lab member comes to understand that only partial modeling of complex activity is necessary or even possible. In this partnership the lab member works with the cells to unlock secrets about the effects of mechanical stress and strain on the life and structure of cells and cell assemblies. Thus we see the construction of knowledge is in partnership with the cells and this partnership is the result of a learning trajectory comprised of changing forms of participation with the cells.

Constructs' as 'Wet' Models and Devices

Members of Lab A use the term 'construct' as a colloquial expression for a "hybrid, endothelial cell-preseeded vascular graft," the artifact Lab A is seeking to develop as a viable substitute for native vessels. As with the cells, we have identified three forms of engagement/interaction with constructs that learners experience as participation grows. These include (1) making the constructs (2) identifying lab members with aspects of the constructs, and (3) working the constructs as models and devices. Understandings of the construct change as the newcomer recognizes certain properties of the construct (1) its "wetness' (2) its primary existence in the plural and its collaborative quality and (3) its engineered properties. Similarly, the learner is differentially implied in these changing categories of interaction: (1) the latex-gloved caregivers and manipulators of biological materials, (2) the lab members participating in a community (3) the designers at their workbenches, whether traditional, bio-safety, or computational and linguistic. Over time, these varied types of interaction cascade into possibilities for partnership with the construct that are enacted through changing interactions and activities with the construct.

Sequentially, learning to make constructs follows learning cell-culturing techniques. *"I finally found a use for all those cells I was culturing"*, one newcomer remarked. Here is how she recounts her first experience building constructs with cells and collagen.

> *"You use these tubes, and you put in, in the cells suspended in the media, and oh yeah, you have to add, like some collagen and some other factors to get it to gel, and they have the little 3 mm glass rods that they've made that will, I guess learn to make at some point, with little stoppers at each end that they use to put in there and um the cells bind that and kind of gel to a nice little construct form"*.

When asked why the construct gels, she responds *"It's due to the additive in there. It causes them to kind of come together. Yeah, I can't give you a really good explanation yet."* Here our learner interacts with the construct and its wetness as the latex-gloved manipulator. She has learned how to build them but falters when asked to explain processes implicit in the device creation. In this preliminary learning phase, the construct is something she creates from components using highly specified steps. The construct is the product of her work under the hood. She will build these repeatedly for practice and later for the experiments she will perform. These interactions and activities characterize her first relationship with the constructs.

In contrast to this account of the construct, a third-year lab member offers another understanding.

> *"…one of the main limitations of the collagen gel construct is its mechanical strength. And like over the course of research in our lab, um, A01 had looked at things like mechanical conditioning to increase the strength, um and of course, A12's work has focused on how he could integrate elastin. Well with his integration of the elastin sleeve we've now actually made enough progress in the area of mechanical strength that we have a strong enough construct to put in an animal."*

This account characterizes constructs as products of communal activity around a problem—lack of mechanical strength. A historical trajectory of the lab is constructed around this artifact giving it meaning through its relationship to the lab members and their different projects. Two prior lab members are referenced and their roles in this problem solving effort are recounted. One person looked at mechanical conditioning as a possible source of strength while another added a new component. Now she identifies her future work and role, which is to test the mechanical strength of constructs in animals, as another chapter in the history of the construct and the lab. The construct here serves as a meaning creating thread that binds the activities of these varied lab participants and which etches out a chronological line of research. In this account, the construct exists in the plural, as a community resource acting as a 'player' in communal problem solving. If pressure is the enemy *in vivo* as blood pulses through an artery, then constructs are partners in conquering this enemy.

After a learner knows how to make constructs and relates in some way to the construct's biography, advanced research activity requires a more involved relationship. A second year Ph.D. student explains her relationship with the construct in this way:

> *"The big, big question is um, how do our constructs as like a modeling tool, how do they respond to or biological markers respond to mechanical stimulation. So is there a certain correlation to the stress and strain and the distribution being applied to these constructs to certain biological markers? So are they being up-regulated? Down regulated? How are they being distributed along the construct? Is this appearing like native vessels?"*

This explanation of the construct implies both the making and the communal qualities already discussed but foregrounds the construct as an engineered model and device. She refers to them as "modeling tools". To understand how this is a partnership, we have to probe the dimensions of a '*tool that models*'. Devices as we encounter them in the lab are at once modeling and model-affording. On the one hand, constructs model a blood vessel which under conditions of mechanical stress and strain are known to change and are also known to have biological markers which can be indicators of that change. But just as powerfully, constructs as devices need to be understood as objects in their own right, which goes beyond their function as model instantiating artifacts. The construct as device has become a site for *in vitro* or biological experimentation on blood vessels, which is akin enough the real thing to serve as proxy. In a real sense, the construct by itself, in its own right, has become an environment for biological inquiry. As such, it is composed of cells that are in themselves environment-creating to other cells embedded in the construct. Thus as devices the constructs are not only subjected to an environment, they are an environment for biological investigations. The student above clarifies the relationship between this proxy environment and the *in vivo* world of native blood vessel as understood by the biologist: *We are hoping that our construct behaves like a native artery because that's one step closer to being functional. So we are kind of doing a mimicking thing. So does it respond in the same manner? That's the big, big question."*

As described in the quote above, the construct is a proxy site for experimentation. Such experimentation always leads back at some point to the overarching goal, which is to translate the lab work into medical applications. The construct as model and device is critical to this endeavor. Once the construct is recognized as an environment in its own right, it becomes a very rich place and system with which the researchers can have dialogue and interaction. In fact, "dialogue and interaction" is also how the researchers characterize what is going on in the construct and between the cells. The researchers in the lab call the process of constructing and manipulating these *in vitro* sites "*putting a thought into the bench top and seeing whether it works or not*." These instantiated "thoughts" allow researchers to perform controlled simulations of an *in vivo* context through a cognitive partnership with a viable cardiovascular stand-in. This level of simulative model-based reasoning represents is a hard won competence deriving from work and failure on the benchtops.

Implications

Our findings from the research laboratories and interviews with biomedical engineers have led to significant changes in the way we scaffold complex problem-solving sessions in our PBL classrooms. In particular, we are foregrounding the importance of models and model-based reasoning both in the development of new problems and also in the forms of classroom support used by the PBL tutors. The notion of cognitive partnering suggests that we need find ways to help students better understand the relationship between models and material artifacts and between the related practices...At a more advanced level, these practices related to the material artifacts acquire a simulative dimension in relation to model-based understanding of systems. For example feeding a cell culture is not just adding media to a culture dish, it is actually simulating a larger physiological system, in aspects salient to the research. In line with others who investigate student understanding of models and their use in science (Grosslight, Unger, Jay, Smith 1991), we find that students need help in moving decisively beyond the idea of a model as a comprehensive real-world replication to notion of model as tool, as an intentionally abstracted focal point for investigation and hypothesis testing. But just as importantly we need to find ways to create educational settings in which the relationship between models and actions and what we have tentatively called cognitive partnering, are foregrounded. The kind of learning we would like to foster is one in which students would experience models both in relations to other models but also as mediators and tools in doing their own work as part of a research community.

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