Cognitive partnerships on the bench top: designing to support scientific researchers

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ABSTRACT

There has been a growing interest to develop technologies for laboratory environments. However, existing systems are under-deployed in real research labs. In order to create more successful technologies for the creative laboratory setting, we need a deeper understanding of the values of the researchers we are designing for and the unique roles of technology in the research laboratory. Our three-year ethnographic study of a biomedical engineering (BME) lab contributes to building this foundation for future design. Drawing form a distributed and situated cognition framework, our analysis highlights the ways in which technology is integrated into the researchers' daily practices. This study is one of the first deep ethnographies of a laboratory culture with a central focus on technology and provides several insights for the design community.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Design, Experimentation, Human Factors

Keywords

Ethnography, Research Laboratory, Distributed Cognition, Appropriation, Creativity, Values

1. INTRODUCTION

In recent years, there has been a growing interest in designing ubiquitous computing systems for research laboratories [1, 11]. Researchers at both Intel and the University of Washington developed the LabScape system, the largest and most well known project in this area. This system, informed by observations of researchers in a biology lab was ostensibly designed to support scientists in their daily work. The observers noted things such as the number of times scientists would move around the room during an experiment. This foundation led them to design a system that primarily focuses on making recording data from experiments easier and more integrated into the laboratory environment via tablet computers. However, in over 3 years of ethnographic study of 2 Biomedical Engineering (BME) laboratories we did not see these types of systems. Part of the reason that these kinds of technologies have not become more commonplace in science and research labs is because these labs are very different from typical work environments. Thus, while HCI has a rich history in designing workplace systems, creative environments such as the BME laboratory challenge the methods used in traditional HCI and the kinds of systems that are developed.

In this paper we present two case studies from our three-year ethnographic study of a tissue-engineering laboratory at a major research university. In section 5.1 we will discuss the "Mechanical Tester," a custom instrument designed and built by BME researchers to determine the ultimate tensile strength of their engineered tissues. Appearing to the computer scientist outsider as somewhat of a hacked together mess, this technology is actually vital to many different lab members' projects and has been established as a key instrument in the lab for several years. In section 5.2 we will discuss a much newer technology, the compression bioreactor. This is an instrument designed to apply compressive forces to progenitor cells in hopes of promoting differentiation into a cell type needed by the researchers. This instrument was still under construction during our time in the lab, and provides a window into how new technologies become a part of the laboratory.

Our goal in presenting these case studies is not to evaluate any one technology. Instead, we use the case studies to characterize the creative environment and illustrate the ways that different types of technology are (and are not) successfully integrated into the everyday practices of the researchers. In this way, we establish the scope and nature of some of the problems facing technology designers. Our analysis of the technology infused research laboratory leads us to two central findings for to technology designers.

First, we find that the values embedded in many existing technologies and design principles do not align with the needs of participants in our study. In particular, increased efficiency is frequently a goal (both explicit and implicit) of technology design generally [7], as well as for systems developed specifically for researchers e.g. [1, 11]. However, we found that the researchers with whom we worked did not appreciate efficiency-promoting interventions – even when we pointed out to them what seems the "obvious" value and they agreed. While the typical workplace may be characterized by repetition of relatively static tasks, the nature of creative environments is one of innovation and change. Therefore, when designing for a creative environment, like the research laboratory, designers should be careful not to over-value efficiency or productivity. Instead, what we found *is* important – and paramount to efficiency or productivity – is that technologies are capable of evolving alongside the changing environment and work practices. Deep ethnography is particularly well suited to uncovering such tacit values and design needs.

Second, we find that part of what underlies the assumptions that efficiency is centrally important, is a notion that a computer is merely a tool – like a calculator – onto which one may offload some mental or physical task. While computing technologies are certainly useful in this way, we found that they are sometimes much more integral to the work of researchers in our study. Some of the more central technologies in the lab environment function as what we term "cognitive partners" in the daily practices of BME researchers. These technologies embody the knowledge and hypotheses of the lab and promote and scaffold scientific exploration and creativity. Considering this more integrative role for technology in daily practice can help designers to create better-suited devices and instruments.

2. METHOD: COGNITIVE HISTORICAL ETHNOGRAPHY

As noted by other researchers [4, 26], technology designers today are commonly using methods from social science disciplines in an effort to better understand potential user groups. Our methodology, cognitive-historical ethnography, draws from work in cognitive science, anthropology, and history & philosophy of science.

To set the stage for our analysis of the laboratory practices, we need to take a brief excursion into the foundations of cognitive science. Traditional cognitive science research attempts to isolate aspects of cognition, such as memory or categorization, to control their investigation in experiments conducted mainly in psychological research laboratories. Although traditional studies are still the mainstay of cognitive science, the last twenty years have seen a move towards investigations of cognition in authentic contexts of human activity such as learning and work. This new research can be characterized as attempting to account for the role of the environment (social, cultural, material) in shaping and participating in cognition. These accounts construe `cognition' as embodied (See, e.g, [3, 14]), enculturated (See, e.g., [22, 24]), and situated (See, e.g., [9, 16]). We call accounts within this emergent research area "environmental perspectives [18]". Such perspectives have also been of growing interest to researchers in HCI-related areas [23, 10].

In contrast to the standard construal that cognitive processes operate on representations "in the head," environmental perspectives maintain that cognitive processes cannot be treated separately from the contexts and activities in which cognition occurs. As Lave contends, "'[c]ognition' observed in everyday practices is distributed – stretched over, not divided among – mind, body, activity, and culturally organized settings (which include other actors)" [16]. 'Cognition,' thus, comprises a complex system, "stretched over" what have customarily been thought of as "internal" and "external" representations and processes.

This study builds on the work of cognitive scientists who take an environmental perspective, in that we view the lab as an evolving cognitive-cultural system. We examine the researchers' problem solving practices as situated in social, cultural, and material environments and as distributed over researchers and artifacts. Cognitive processes cannot be treated separately from the contexts and activities in which cognition occurs. Therefore, our analysis has focused not only on the researchers practices, but also on the technological artifacts that push research activity and are shaped and re-shaped by that activity.

We are examining multiple 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 [12] and 'cognitive artifacts' are material media possessing the cognitive properties of being, generating, or manipulating representations.

However, we find in thinking about cognition as it functions in this lab that current conceptions of distributed cognition in the literature are not fully adequate in that their methods 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 [12], 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. All the components of this kind of cognitive system undergo progressive change. The technology and researchers have evolutionary trajectories that must be factored into the understanding of the cognition at any point in time. Our analysis of the cognitive-cultural systems in the lab as evolving adds a novel dimension to thinking about distributed cognition, and also to methods for studying such systems.

In carrying out a long-term investigation of this type of system a mixed-method approach is required. We conducted both ethnographic studies of the day-to-day practices and "cognitive-historical" analysis [17] of the problems, artifacts, and models employed in research. The ethnographic part of the study (observations and interviews) seeks to uncover the activities, tools, and interpretive frameworks that support the research as they are situated in the on-going practices of the community. The cognitive-historical part of the study included collecting data from traditional historical sources, including publications, grant proposals, laboratory notebooks, and technological artifacts. In doing so, we aimed to capture the diachronic dimension of the research by tracing the trajectories of both the human and technological components of the laboratory.

3. THE RESEARCH LABORATORY

Our research group has studied three interdisciplinary laboratories, however, for this paper we will focus on one site, a tissue-engineering laboratory, "Lab A." Lab A has a broad goal of developing a method for engineering living, cell-based blood vessel substitutes which may be implanted in human patients, for example, as a part of by pass surgery. Ongoing research in the lab is quite diverse, ranging from the "basic science" of understanding the function and behavior of the different cells that make up the cardiovascular system to working out the mechanical issues involved in artificially growing a three dimensional living tissue.

Figure 1: A hood in one corner of Lab A.

While these are "engineering researchers," they work in a space that shares many similarities with the lab studied in the LabScape project. They work with cell cultures and dishes in a space full of hoods, incubators, test tubes and microscopes. Mixed into this environment we find myriad computing technologies.

As STS researchers have established previously [5, 13], we found in our study that BME research does not proceed down a neat and orderly trajectory as in the idealized model of "The Scientific Method." In the real laboratory, experimental practices are not stable and hypotheses are rarely well formed at the start of a research project. However, this characterization of scientific practices does not seem to have made it much beyond these social science fields and so we to briefly address it here.

Although there are standard protocols for simple assays, the experiments that make up the heart of the researchers' work involve much more fluid activities. In the cutting-edge research laboratory, the work of the researchers includes the creative process of coming up with and establishing new practice. This is especially true of the kinds of interdisciplinary research laboratories that we study, where the over-arching agenda is design and re-design of hybrid bio-engineered devices for conducting experiments. Many experiments begin without a well-formed, clearly defined hypothesis, and the researchers themselves will often say that they have no hypothesis at all, much less a detailed plan of action for an experiment. As outsiders we may be able to construct hypotheses for them, working backwards from what they are doing, but it's important to note that they would not do so on their own.

As designers, it is crucial that we understand how existing practices work in order to create new technologies that will be successful in the laboratory. We need to be aware of our preconceptions about scientific method as we conduct ethnographic observations. A system designed around hypothesis testing or strict experimental design as taught in textbooks would not function in the BME laboratory as we observed it. Rather, any technology designed for this kind of environment must be built with the fluid nature of the practices it must support in mind. As researchers innovate and gain new knowledge, technologies and practices must co-evolve to reflect the shifting knowledge base and adapt to the new questions the researchers seek to answer.

4. TECHNOLOGY IN THE SCIENCE LAB

We will first overview of the kinds of technology in the lab before presenting detailed case studies of two specific technologies. The researchers in Lab A come from a variety of backgrounds, but most are engineers of some kind. The objective of the educational environment in which the Lab is situated is to create truly interdisciplinary researchers, biomedical engineers who are integrative thinkers. The nature of the research problems being addressed demands that the researchers both understand and work with complex biological systems as well as understand, design, and re-design complex engineering systems.

Along with learning sterile technique and cell culturing, getting an education on the devices is also a part of becoming a member of the lab. One of the researchers reflects this requirement as she discusses the process of entering the lab, "as a new student in the lab you want to understand what's been done, so, understanding the equipment that is used and how people derive their results is super helpful in [thinking about] what you're going to do for your own project – if you're going to use similar tools and improve them or build upon what's been done." That is, defining one's research is equally about determining the technologies that will be used as it is about defining a specific question with respect to the cardiovascular system. Researchers must understand what has come before and appropriate design history as they construct new devices and modify existing ones. Problems lend themselves to certain technologies, but the technologies also shape the kinds of questions that may be asked as well as how the researchers will answer them. In this environment where work, learning, and innovation are tightly coupled, technology becomes more than simply a tool to accomplish some task, rather, it is tightly integrated into the laboratory practices of innovation and learning.

During the first year of our ethnography in Lab A, we had the scientists perform a card-sorting task to help us understand the different kinds of technology in the lab. During a research meeting with the laboratory members, including the PI, we asked them to sort the material artifacts in the laboratory according to categories of their own devising and rank the importance of the various artifacts to their research. Their classification in terms of 'devices', 'instruments' and 'equipment' is shown in Table 1.

Table 1: Categorization of Technological Artifacts

Devices	Instruments	Equipment
The Flow Loop	Confocal Microscope	Pipette
Equi-Biaxial Strain Device	Flow Cytometer	Flask
Construct	Mechanical Tester	Water Bath
Pulsatile Bioreactor	Computer	
	LSM 5 (Computer Program)	Camera

Based on our, additional ethnographic observations and interviews we have formulated working definitions of the categories employed by Lab A's researchers. In our analysis of the lab we find that the *devices*, in particular, are significant cognitive artifacts. As engineered facsimiles, they serve as in vitro models and sites of simulation. *Instruments*, some of which can also perform as cognitive artifacts, extract and process information, generate measured output, and enable simulative manipulation. Only *equipment* serves merely to assist with manual or mental labor.

Most off-the-shelf purchases that the lab uses fall into the equipment category. Devices and Instruments, on the other hand, may be purchased, but more commonly are highly customized technologies, or even made entirely in-house. These custom technologies will eventually become sites of experimentation where researchers will manipulate living cells and tissues. However, the process itself of creating or customizing technologies is important as a way for the researchers to explore and deepen their own understandings not only of physics and engineering concepts but also of the *in vivo* world they are simulating. In this sense, designing and building these technologies is also an important site of experimentation. Creating a new instrument or device is a way of embodying one's ideas and hypotheses, and exploring them within the constraints of the physical world.

The researchers embed in these technologies much of their understanding of tissue engineering and blood vessel dynamics as well as their experimental hypotheses. Thus, lab members must create and continually refine these devices and instruments as they make advances in knowledge and evolve their scientific practice.

5. CASE-STUDIES

The way that researchers worked on two of the fundamental problems for the lab demonstrates the specific ways that technology functions in the lab. In the following two sections, we will overview the problems faced by the scientists from a research standpoint and then we will elaborate on two successful technologies designed to solve these problems – the mechanical tester and an un-named bioreactor, which we call the "compression bioreactor." A "bioreactor" is, as one lab member explained, "anything that does something to a tissue or a construct[1] containing cells," where "doing something" means applying some force (e.g. compression).

Both of the instruments that we will be discussing belong to the class of devices and instruments called "bioreactors." The Mechanical Tester (MT) is an instrument that pulls the lab's tubular constructs apart until they break to test the ultimate tensile strength of the cell matrix. The compression bioreactor, applies the opposite force. Its purpose is slightly different, however, in that it does not test some features of constructs to see how similar they are to real blood vessels. Rather, it compresses engineered tissues containing progenitor cells with the hope of altering the cells – coercing them to become more like mature blood vessel endothelial cells. While this particular bioreactor was not in the lab at the time of the card sort activity, we presume that the scientists would have classified it as an instrument. Unlike the pulsatile bioreactor, a device, the compression bioreactor was not designed to simulate some *in vivo* process, but rather to manipulate cells and promote changes in a contrived manner. Thus, although it does embody some knowledge or at least a hypothesis about stem cell differentiation, it is less like the devices in that is not meant to be an engineered *facsimile*.

5.1 The Mechanical Tester

In their work to create blood vessel substitutes, the scientists still struggle with fabricating a construct that can withstand the intense forces generated by a pumping heart. In the service of testing varied constructs for strength, the lab has developed what they call the mechanical tester (MT). We previously thought that a new device made by the Instron Company and purchased by the lab in 2002, would replace the MT [19]. However, years later, the Instron sat on a shelf in the back of the lab, playing no role in mechanical testing, while the MT remains in near-daily use, and is located centrally in the scientists' workspace.

Figure 2: The two halves of the Mechanical Tester. On the left are various cables, a voltage meter, and the PC that serves as the main output. On the right is the instrument itself. Compare to Figure 3.

The MT is a clunky cobbled-together looking piece of technology. It has a long history, originating in a lab down the hallway and moving to Lab A when an ambitious graduate student saw the potential for using it in his own work. Today the instrument consists of a variety of components, added by students and researchers over the years. Essentially there are two main parts – a typical desktop computer sits on the bench top to the left and then the site of experimentation – the stretching hooks and accompanying sensors – are off to the right, on a low shelf. Between the experimentation site and the desktop computer are a variety of cables and a video camera. A voltage meter is even perched atop a shelf on the bench top lending an extra display.

In order to use the MT, the researcher first takes her constructs and slices them into small rings onto which she glues small black beads. The mechanical tester has two hooks, submerged in a chamber filled with liquid, and using calipers, she gently attaches the construct ring to each hook. Then, the researcher must calibrate the video camera (using a ruler and the computer monitor), open several command prompts on the Windows PC and then simultaneously start multiple programs. After the MT breaks the ring by pulling the two hooks apart, the user will move output values (data from a video analysis program as well as data from the voltage meters) into an Excel spreadsheet and then use a series of custom macros to manipulate the raw data into

[1] "Construct" is the term that the Lab A researchers use to describe their *in vitro* models of blood vessels. One objective of the lab is improving the construct to share more properties with *in vivo* blood vessels.

something more meaningful. The researcher repeats this process for each ring. She also needs on hand a pen, some printed sheets for recording intermediary data, and a hand held calculator… and some snacks – one experiment takes 40-60 hours all total.

Stress, strain, and ultimate tensile strength – the values that the MT measures – are standard tests performed in Mechanical Engineering among other fields. In 2002 the lab decided to buy a machine to replace the MT. They decided on one built by the Instron Company, and spent quite a bit of money on a used one.

The instrument has an integrated keypad and limited display mounted just next to the experimentation site, and displays more detailed output on an attached PC. It is basically "better" than the MT in every measurable way. It has a cleaner interface; it's easier to use and to learn to use; it's more efficient; it generates data that is both more accurate and more precise; and it even spits out numbers in a variety of ready-to-use graph and table formats. The researchers recognize these strengths and describe the generic software that it came with as "nice" and a "piece of cake" – probably not how anyone would describe the custom software that operates the Mechanical Tester.

However, the Instron never replaced the Mechanical Tester, and now that we have a better understanding of the creative space of the laboratory environment, we can understand why. It does not integrate well into their existing practices, defined over many years in response to research questions as well as more pragmatic issues of dealing with 3-D engineered tissues. The following conversation between two researchers demonstrates that the gains in efficiency, accuracy, and ease of use of the system do not make up for the lack of integration into existing practices. The conversation started when an undergraduate researcher said to a more senior lab member "I don't know why you guys don't mechanical test [with the Instron]"

> **Senior Lab Member (S):** So, you know, we need a bottom hook. You know, right?
>
> **Undergraduate (U):** And you need the…
>
> **S:** Our system [the mechanical tester], the hook, you know, moves at the bottom. It moves on the bottom, so to change it to the top… but it [the hook] needs to be enclosed. So the thing is how do we get in there to load it, if we have the bottom hook stationary, so we need it to where it will remain. It needs to remain

At this point the undergraduate started to see the problems that would require significant changes to the machinery of the Instron if it were to replace the MT, but he tries to suggest ways of fixing them.

> **U:** Ooh yea
>
> **S:** And it has to
>
> **U:** So you need like a door that you can open and then close it
>
> **S:** Yea, but—
>
> **U:** [And you'd need] a gasket and fill it

And then his inexperience with the detailed established practices of the lab begin to show.

> **S:** So the thing is loading it is really hard, you need the solution to load it, to help it, [the construct] open back up.
>
> **U:** Oh really?
>
> **S:** So I don't know if you use our tubes
>
> **U:** I don't do tubes
>
> **S:** Our tubes are kind of weak, so when you take them out of water, they do this, (claps hands) go like that
>
> **U:** Since they're wet, they just kind of stay
>
> **S:** So that's why we actually fill the chamber first, let it open up, and then put it on, so that's why we kind of been avoiding this thing [Instron], cause no one wants to design something that'll work. So I mean, ideally, our arm is not going to go up to the top
>
> **U:** Just build a big cage for it [The entire Instron] and you can turn it the other way
>
> **S:** Rotate it as needed.
>
> **Both:** (laugh)
>
> **S:** So yea, that's the issue, I think that [Researcher2] you know was the one that ordered it and she was all gung-ho about it, and then it kind of got passed on to me, maybe if I do a fixture, and then [Researcher3] got here and she was like oh yea I can
>
> **U:** You guys are all mechanical engineers. You should figure something out.
>
> **S:** I know that's what we were, all say, oh ME [Mechanical Engineers], oh no, well [Researcher2]'s not an ME, we said oh yea we can do this and this and oh yea we can do this, and then, you know, you see what's happened. It sounds easy, and it sounds really cool, but…

Although the machine works for tensile tests of just about any material, it does not work for "our tubes." In all of its clean black-boxed beautiful design, it is closed off to the researchers and their need to appropriate it and integrate it into their own work, and for no lack of ability, inexperience or effort on their part. These are people trained in mechanical engineering, among other fields, who have built numerous complex devices for the lab, but modifying the Instron proves to be too difficult a task.

In conclusion, the scientists are both unwilling and unable to change their practice to match the requirements of this nice fancy new technology. They embed much more than the specific hypotheses they are testing in the devices and instruments that they build. The technologies are embodiments of all of the knowledge and practice that intersect at the site of experimentation. In the case of the mechanical tester, its design has roots in both the in vivo and in vitro worlds of the researchers. They use it to see if their constructs could withstand the forces of human cardiovascular system (or if they at least getting closer to that goal). When they decided that testing local strain might be more beneficial than their original single measurement, they added a video camera to the MT and small black beads to the construct to allow them to test strain along the sides of the construct as different from strain at the hooks. It must be able to work with their constructs, and all of the limitations that come with. The original MT, while a jumble of parts and "difficult"' to use, has evolved over time along side the lab's changing practice and knowledge in a way that the Instron seems not to fit in. That is not to say that no outside technologies can fit into the lab. A standard desktop PC is, after all, a major component of the MT. However, technologies that will be successful in creative environments must support the kind of evolution and appropriation that users demand from their tools, and, as we show next, the researchers appropriated the Instron for use in answering a new research question, though in a quite different way from the original intention in purchasing it.

5.2 Designing a Bioreactor

Another fundamental problem for the lab is coming up with a source for a large number of endothelial cells – the special cells that line every blood vessel in the body and regulate clotting. In order to combat rejection complications involved with implanting fabricated blood vessels into a human body, the researchers would ideally like to devise a way to obtain cells directly from a prospective patient.

One potential source is the endothelial progenitor cells that, at varying stages of development, are either in the bone marrow, or circulating in the body's blood. A researcher described these to us as "like an adult stem cell." That is, they are not stem cells as we discuss in the popular news, that may differentiate into any cell, but rather, they are already on their way to becoming a blood cell, but all of the characteristics of endothelial cells are not yet developed, and they do not function properly if embedded in construct walls as immature cells. One of the post-doctoral researchers in the lab has been successful in devising a way to cause the differentiation, however, the process is tedious, labor intensive, expensive and thus impractical – "you're not gonna see, an implant company doing that." After reading about researchers at another institution who were successful in causing differentiation of other cells into ligament tissue via the application of mechanical forces, two researchers in Lab A set out to see how mechanical forces would affect their marrow progenitor cells.

The focus of our analysis is data collected about a pair of students engaged in building a new "bioreactor" – or *in vitro* experimentation device. A31 was a senior undergraduate student during the time when ethnographers were working in the lab, and A26, his mentor, was a post-doctoral researcher who also had industry experience prior to entering this laboratory. A31's project was to build a custom bioreactor that would allow the researchers to explore the effects of compression on stem cells.

We might say that A31 and A26 hypothesized that the application of various mechanical forces (in this case, compression) will cause the progenitor cells to differentiate into the special endothelial cells; however, they themselves would not make such a statement. When asked relatively early in the project why he is applying compression forces in particular, A31 replied that he had been instructed not to answer that question, because they did not really have "justification" for their research. In an interview soon after this, when he was pressed by the interviewer, "Is it safe to say you have a hypothesis?" he replied, "[sigh] We don't really, no. [laughs] To be honest, we want to come up with a process that could ultimately generate a high yield of endothelial cells. Whether or not that's possible – don't know. I think it could be, but I think it may depend on a combination of physical forces and biochemical cues." At this stage, when A31 was already part way into designing the new bioreactor for the lab, he and his mentor still had neither a detailed plan nor a well-formed hypothesis for what they were doing.

Over the next several months A31 and A26 refined their plans as they learned through the design and building process. Designing and building the bioreactor was an ongoing evolutionary process that scaffolded learning and knowledge development, which in turn, shaped the continued bioreactor development. A31 actually built two related bioreactors for this experiment. One bioreactor, the "confined compression" bioreactor appropriated the existing Instron machine and served as a test bed for a second, "unconfined compression" bioreactor that was built from scratch. For clarity, we will refer to these as the "modified Instron" and "custom bioreactor" respectively.

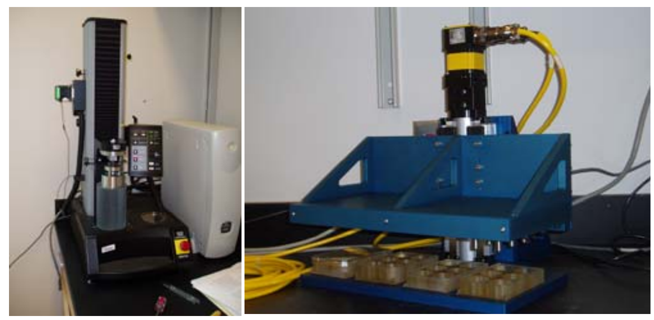

Figure 3: The two compression bioreactors. On the left is the modified Instron machine – with a riser block and compression chamber. On the right is the custom-designed unconfined compression bioreactor near completion.

In addition to designing the mechanical and computational aspects of both biroeactors, A31 also had to devise the biological, tissue-engineered constructs that could be used for the experiment. His goal was to apply compressive forces to cells, which had to be embedded in some kind of scaffolding material. Initially, he planned to grow the endothelial progenitor cells in collagen. This is the material that cells grow in in the human body and as such, it is the typical matrix material used by the lab in their research. However, midway into designing how he would form discs of an appropriate size and shape for the bioreactors that he was concurrently designing and building, he realized collagen wouldn't work:

> **A31:** OK, we're trying to investigate the effects of compression on um stem progenitor cells in a 3-dimensional construct, but we were planning on using – we, we do most of our work with collagen gels and so near the end of last semester I was just you know trying to figure out how- what was the maximum load we could apply to the collagen gel before it ruptured. So I put a couple of `em out on the bench top and I put – and I got all these weights out – you know and I had a plastic clear uh plate I put over them, and as soon as I put the lid on it – just the plastic plate I mean – it was the lid of a tissue culture dish, it uh – and its probably less than 50 grams – it flattened the gels so thin that you know the ridge of the the lid was sitting on the table and the gel deformed all the way out like this.

Interviewer: Oh my goodness! Were you expecting that?

A31: No. Not at all [starts to laugh]

Interviewer: What did you think was going to happen?

A31: I figured it would, I figured, have you ever pressed on a piece of Jell-O?

Interviewer: Sure!

A31: I figured it would it would kinda deform a little bit and crack and tear. The problem with that, since we found that out, its now we can't do unconfined compression with collagen, and most of our work is done in collagen.

This almost accidental discovery of collagen's mechanical properties is typical of the kind of exploration and discovery that is ongoing in this kind of research environment. In this case, the new knowledge changed A31's plan from simply designing a bioreactor to also testing new kinds of scaffolding material not currently used in the laboratory. While he worked out how to grow the cells, bioreactor development continued, with the understanding that "we have to find a scaffold material we can use it with, otherwise it's really of no use to us." After several weeks of experimentation, the researchers found a mechanically suitable matrix material – alginate, a polymer derived from seaweed – and using the bioreactors became a real possibility.

Our observation of the researchers using the modified Instron bioreactor for the first time again highlights the fluid, evolving, and exploratory nature of laboratory. At this point, A31 and A26 had been working on together for over six months, designing and building the two bioreactors. On this day, the last of the custom parts for the confined compression bioreactor had been assembled, and A31 had a set of gels (cells in collagen) ready for experimentation. Our ethnographic field notes recount the first assay:

The first gel doesn't get squished. On a second try, it gets squished so much that it sort-of comes up and out the sides, and the Instron's self-protection mechanism causes the machine to beep loudly and immediately shut itself down because too much force was being applied. The next few go somewhat more smoothly, but these first few runs don't produce much (if any?) usable data. However, they are clearly important for both A26 and A31 to learn how to use the bioreactor.

Even after spending countless hours designing this machine, neither researcher had a very detailed plan going into the experiment of what would or should happen. Although there are some laboratory procedures that are more established, and have a "protocol" sheet stored in a bound notebook at the front of the lab – carrying out one of these basic assays is the easy part of the researchers' work. Discovery and progress center on leaping from the edge of established knowledge, and leaving an historical record that allows others to follow in those footsteps.

The modified Instron, though initially easier to modify and temporarily a focus of work, was pushed aside for the more complex custom bioreactor that the researchers could better integrate into their work. The custom unconfined compression bioreactor was designed so that it could be placed in an incubator for more sterile and controlled tests (e.g. at physiologic temperature) than the Instron, which must sit out in the open lab space. The initial modified Instron, however, served an important, even if temporary, role. In designing fixtures for the appropriation of the Instron, A31 learned valuable concepts about mechanics and engineering through exploration and tangible experience. Furthermore, the researchers were able to use this modified Instron for "preliminary trials" that facilitated development of new knowledge related to how one can set up a compression experiment with cells embedded in engineered tissue. The knowledge gained from designing and using this instrument was later embedded in the unconfined compression custom bioreactor. The intermediary instrument, thus, served as a stepping-stone and tangible test-bed for ideas and hypotheses.

This is what often makes bioreactors so powerful for researchers – they scaffold exploration. In this case, the bioreactor allowed researchers to embody their tentative ideas and evolving knowledge of mechanics, biology and cell development. Beyond what the bioreactor does to the cells (hopefully, perhaps, it will cause differentiation) the bioreactor also does something for the researchers' knowledge and practice. In the space of the laboratory, the bioreactor is a physical and tangible articulation of the researchers' understandings and objectives. A limited kind of reciprocity emerges in this relationship between the scientist and the instrument. The technology's actions, sometimes surprising, teach the researcher about what he has built and how he may best use the technology. The bioreactor can serve to help formulate, validate or invalidate the researchers' hypotheses and knowledge because it exists in the real world that the scientists could not fully explore with thought experiments alone. Constructing and then using the bioreactor forces and scaffolds the construction of more concrete knowledge. The design and building of instruments can be an experiment in itself, long before the bioreactor is used as an instrument for manipulating cells in some type of assay.

6. IMPLICATIONS FOR DESIGNERS

In this section we will continue the discussion from our case studies with a focus on the implications of our work for technology designers.

Designing for creative environments challenges traditional notions of human-computer interaction and even some user-centered design techniques. Traditional approaches typically focus on getting to know a user group via observations, interviews, surveys or focus groups. Some methods closer to our own include design ethnography and participatory design. However, the goal of much user research, regardless of methodology, is often to "define" the target population and identify some set of tasks that can be translated into system requirements. Design is about supporting these requirements, and to that end, it typically centers on making more efficient the particular set of tasks or interactions uncovered by the initial research. Although this approach may be successful for supporting specific and relatively static practices in typical work environments, the evolutionary nature of creative environments requires a new approach. In order to successfully design technologies that promote and support creativity, designers need to reconsider the assumed relationships between humans, technology, and practice that underlie the standard user-centered design process.

6.1 Values in Technology Design

As the work of researchers in a wide variety of areas suggests (e.g. cleaning products in the home [26]) the next big challenge for technology designers is to consider the variety of values embedded in existing technologies and practices when creating something new. Technology deployment has multi-faceted implications, and designing primarily for increased efficiency, productivity, or reduced effort in one area of an existing practice, may have broader impacts that do not necessarily improve the overall situation.

6.1.1 Efficiency is Not a Central Problem

Science and engineering researches in creative and innovative environments by-and-large do not care about efficiency. In beginning to think about how information technology might be designed to support and facilitate research in Lab A, we asked the laboratory manager – who is intimately involved with and knowledgeable about the research – if he thought a system such as LabScape [1] would be useful in his lab. As mentioned earlier, Lab A appears similar to the cell biology laboratory studied in the LabScape project, and the researchers are familiar and comfortable with computing technologies. Thus, we were somewhat surprised when the he said that he saw no value in a system such as LabScape for his laboratory. Now that we have a better understanding of the culture and practices of the laboratory, we can see why. Although the design of LabScape was grounded in an ethnographic-style study, the researchers focused on issues like "during the sixty minutes, the biologist changed locations a total of 76 times [1]." Inefficiencies were assumed to be `bad' and `science' was assumed to always progress like a well-structured assay. These values that were embedded in the system do not align with the values of our participants.

LabScape was designed to support the "everyday work" of scientists in so far as this work was a planned and carefully executed experiment. The system centers on the use of Sample Flow Graphs (SFG): detailed experimental plans in the form of a kind of flow chart. Throughout an experiment the biologist logs her work by noting where she is in the task flow, and the outcomes of each mini-step. At the end, her plan has seamlessly morphed into a report that can be transferred to a lab notebook, for example. In our observations of Lab A, we find that research practice rarely proceeds in such a neat or tidy fashion. Following a protocol for an experiment is only a very small portion of what scientists do every day. Rather, as the case study of the compression bioreactor demonstrates, scientific practice is often much more exploratory and evolutionary in nature.

Furthermore, as Wyche, Sengers & Grinter noted in their household cleaning study [26], gains in efficiency or productivity may have unintended negative impacts beyond the initial problem space. While clothes dryers freed women to spend more time elsewhere, it removed a valuable opening for casual social interaction with neighbors. Similarly, in the science lab, while automated recording or data capture may help scientists be more efficient or take fewer trips across the laboratory space, it removes some of the serendipitous collaboration and built in checks for their work. Small mistakes are frequent as researchers do math on the fly, converting from past experiments and published standards to the current situation. If a researcher has to record a value once on scratch paper and again back at his computer, he may be more likely to catch a mistake. If someone needs help recording information at the hood so that her hands remain sterile, then she has another pair of eyes watching her work and another person's knowledge and ideas available.

Thus, efficiency is not paramount in the environment. Not only because there are few stable practices to make efficient in the first place, but also because changes in practice could have potential negative consequences beyond their intended scope. Some of the inefficiency builds valuable research checks into the typical practice.

6.1.2 Inflexible Practice and Appropriation

An especially salient characteristic of the research lab that we observed, and we presume of many creative environments, is that while practice is generally evolving, it is also, perhaps surprisingly, inflexible. As we saw with the Instron and Mechanical Tester, while some technologies may be well suited to a specific problem, that does not ensure their successful incorporation into research practice.

Because the development of new knowledge and new practice requires the ability to try out new ideas, technologies that will be successful in a creative environment must support exploration and have the capacity to co-evolve with research practice. In order for technologies to co-evolve with changing practice, scientists must be able to appropriate them for novel uses. Designing for one specific interaction or task constrains the possibilities for use, and severely limits the success of a technology in an evolving setting. Here, we would like to build on Dourish's notion of 'appropriation' as "the way in which technologies are adopted, adapted, and incorporated into working practice" as a key characteristic of technologies that can promote creativity [6]. To this we add the notion of appropriating the history of the design of a device and its use in problem solving.

6.2 Cognitive Partnering

One objective of the emerging field of Human-Centered Computing is to articulate and develop new ways of understanding the human-technology relationship. For all three laboratories that we observed, and presumably in other creative environments, technology plays a greater role than simply as a tool for offloading some task. Technology can be a partner in creativity if it supports the values relevant to innovators.

When we look at the roles that the Mechanical Tester and bioreactor play in the practices of researchers in Lab A, we can see that they are central to all aspects of work, learning, and innovation. They are typical technologies in that they can be used to take some input, manipulate it, and reduce some output. In this work sense, then, the interaction pattern fits well within the models of technology use as seen in most of HCI (e.g. [20]). A popular textbook in HCI [5] describes the human-technology relation as a four-component model that explicitly incorporates the system into the relationship. However, even in the textbook model, keyboards and monitors divide the user and system from one another, and interaction focuses on an exchange of inputs and outputs with processing (cognition) isolated in the technology and the human, independent of one another. When we look at how technologies are integrated into creative environments and practices of learning and innovation, these models no longer seem sufficient for describing the entirety and complexity of the relationship.

The central purpose of the technology is often not what it "does" for the researcher, but how it enables the researchers to embody and test hypothetical models of biology and mechanics. We use the notion "cognitive partnering" to capture our observations that the researchers understand and interact with the technology they design and construct as though they were collaborators in research [21]. For instance, in the bioreactor case, the design and construction of the instrument helped the researchers define their questions and deepen their knowledge – the technology itself was a site of exploration and experimentation.

What is important to note here is when the scientists use the technology to manipulate cells it is not just the final assay which can be examined to test their original hypothesis that contribute to knowledge creation. Rather, learning and knowledge innovation occur through the entire process of building and designing the bioreactor. The bioreactor is not a "system" separated from the user by its available inputs and outputs, but rather it is more like a partner in that it supports and promotes creativity by being a site of exploration and discovery.

The researchers call what they do in simulation and experimentation "putting a thought into the bench-top to see if it works." From a distributed cognition standpoint, as an instantiated thought, the bioreactor is an embodied "mental" model – a tangible artifact with a meaning that evolves alongside the scientists' understanding. It thus serves an important function as a site of simulation – not just of some biological or mechanical process, but also of the scientists' knowledge.

A model of technology interaction based on *partnering* suggests different places for breakdowns than the traditional HCI models. In addition to breakdowns that may occur between the inputs/outputs and human and computer on either side, we find that breakdowns may occur when the device does not align, or, more importantly, is not capable of re-aligning with the models of the user. In particular, in the research lab, we find that breakdowns occur when a technology does not support appropriation and cannot evolve with knowledge innovations.

7. CONCLUSION AND FUTURE WORK

In this paper we have shown how and why some technologies work and others fail in the engineering research laboratory. In addition to the implications for designers that we discussed in section 6, we also gave a full description of the interaction patterns surrounding certain technologies and the way that these technologies are integrated into the creative practices of the research laboratory. In doing so, we aim to provide something more useful than a single design idea. Hopefully we have built a piece of the foundation upon which other designers can create a wider variety of innovative technologies than we, as primarily ethnographers and cognitive scientists, could envision alone.

While earlier attempts at designing technology for the laboratory may be under-deployed and under-used, we believe that there is the potential for very valuable technologies to be developed for the scientists. Building on our ethnographic study of the research labs, we have ideas for what problems are very real to the scientists, and how we can better embody their values in the technologies that might be created.

Although LabScape makes following a protocol and recording data more efficient, this "problem," when viewed with respect to the environments we study, is one of computer scientists, not biologists and engineers. These researchers do, however, struggle with how to generate hypothesis, how to build new technologies, how to augment existing ones, how to know what came before and what's going on next door, how to leave a bioreactor – that you only just figured out yourself even after spending 6 months personally designing it – in such a way that other researchers who come along later can know what you have done and why, and see the potential for using this device in their own work. At the same time, researchers do not want to devote large amounts of time to writing up instruction manuals. Building on the WikiTUI project [25], we envision as one example of a promising technology to be a kind of "annotation space" where researchers could bring a physical device, and then "tag" different areas of the technology with their knowledge in the form of video, audio, or written data. In this way, design decisions and knowledge could be embedded into the technology in a way that was retrievable by other researchers at a later date.

Furthermore, while we note that the process of building bioreactors and other technologies is an important process for the researchers, it is also a difficult one. It would not, perhaps, be useful to have an outsider come in and build a device *for* the researchers, however, research along the lines of the Phidgets project [8] provide promise for allowing the scientists to retain control over the important experimental process of designing and building a custom device while not having to invest large amounts of time in learning the details of electrical, computational and mechanical systems.

Finding the problems that are real to a population and creating technology that really works for people will always be a challenge. We believe that methods like participatory design and ethnography can help designers better understand their users. However it is tempting to use these methods simply to discover where people's work may be inefficient. When using ethnography and similar methods, it is crucial for researchers to de-familiarize themselves not only from the environment under study [2], but also from typical computer science problems like efficiency and productivity. In creative environments like the science lab, other factors, such as those that we have discussed are far more important for the success of a new technology. Furthermore, especially in environments where technology is custom made, it may serve a more integrative role than a simple "tool." Considering that devices and instruments can function as cognitive partners highlights different aspects of the technology as important. De-familiarization and deep ethnography can help researchers to better understand a culture that they are designing technology for and environmental perspectives on cognition similarly encourage a holistic view that can highlight new roles for technology like cognitive partnering in the research laboratory.

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9. REFERENCES

[1] Arnstein, L., Hung, C., Franza, R., Zhou, Q. H., Borriello, G., Consolvo, S., and Su, J. 2002. Labscape: A Smart Environment for the Cell Biology Laboratory. *IEEE Pervasive Computing* 1, 3 (Jul. 2002), 13-21.

[2] Bell, G., Blythe, M., and Sengers, P. 2005. Making by making strange: Defamiliarization and the design of domestic technologies. *ACM Trans. Comput.-Hum. Interact.* 12, 2 (Jun. 2005), 149-173.

[3] Clark, A. 2003. *Natural Born Cyborgs: Minds, Technologies and the Future of Human Intelligence.* Oxford University Press, New York.

[4] Crabtree, A., Benford, S., Greenhalgh, C., Tennent, P., Chalmers, M., and Brown, B. 2006. Supporting ethnographic studies of ubiquitous computing in the wild. In *Proceedings of the 6th Conference on Designing interactive Systems* (University Park, PA, USA, June 26 - 28, 2006). DIS '06. ACM, New York, NY, 60-69.

[5] Dix, A., Finlay, J., Abowd, G., and Beale, R. 2004. *Human-Computer Interaction.* Pearson, Harlow.

[6] Dourish, P. 2003. The Appropriation of Interactive Technologies: Some Lessons from Placeless Documents. *Comput. Supported Coop. Work* 12, 4 (Sep. 2003), 465-490.

[7] Frøkjær, E., Hertzum, M., and Hornbæk, K. 2000. Measuring usability: are effectiveness, efficiency, and satisfaction really correlated? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (The Hague, The Netherlands, April 01 - 06, 2000). CHI '00. ACM, New York, NY, 345-352.

[8] Greenberg, S. and Fitchett, C. 2001. Phidgets: easy development of physical interfaces through physical widgets. In *Proceedings of the 14th Annual ACM Symposium on User interface Software and Technology* (Orlando, Florida, November 11 - 14, 2001). UIST '01. ACM, New York, NY, 209-218.

[9] Greeno, J. 1998. The situativity of knowing, learning, and research. *American Psychologist*, 53, 1, 5-26.

[10] Hollan, J., Hutchins, E., and Kirsh, D. 2000. Distributed cognition: toward a new foundation for human-computer interaction research. *ACM Trans. Comput.-Hum. Interact.* 7, 2 (Jun. 2000), 174-196.

[11] Hughes, G., Mills, H., De Roure, D., Frey, J., and Moreau, L. 2004. The semantic smart laboratory: a system for supporting the chemical eScientist. *Organic Biomolecular Chemistry* 2, 22, 3284-3293.

[12] Hutchins, E. 1995. *Cognition in the Wild.* MIT Press, Cambridge.

[13] Knorr-Cetina. K. 1999. *Epistemic Cultures: how the sciences make knowledge.* Harvard University Press, 1999.

[14] Lakoff, G. and Johnson, M. 1998. *Philosophy in the Flesh.* Basic Books, New York.

[15] Latour, B. and Woolgar, S. 1979. *Laboratory Life: The Social Construction of Social Facts.* Sage.

[16] Lave, J. 1988. *Cognition in Practice: Mind, Mathematics and Culture in Everyday Life.* Cambridge University Press: New York.

[17] Nersessian, N. J. 1992. How do scientists think? Capturing the dynamics of conceptual change in science. *Cognitive Models of Science* 15, 3-45.

[18] Nersessian, N. J. 2005. Interpreting Scientific and Engineering Practices: Integrating the Cognitive, Social and Cultural Dimensions. Chapter in *Scientific and Technological Thinking.* Earlbaum. 17-56.

[19] Nersessian, N. J., Kurz-Milcke, E. and Davies, J. 2005. Ubiquitous Computing in Science and Engineering Laboratories: A case study from biomedical engineering. Chapter in *Knowledge in the New Technologies.* Peter Lang Publishers, Berlin. 167-198.

[20] Norman, D. 2002. *The Design of Everyday Things.* Basic Books, New York.

[21] Osbeck, L. and Nersessian, N. J. 2006. The distribution of Representation. *Journal for the Theory of Social Behavior* 36, 2 (Jun. 2006), 141-160.

[22] Shore, B. 1997. *Culture in Mind: Cognition, Culture and the Problem of Meaning.* Oxford University Press, New York.

[23] Suchman, L. 1987. *Plans and Situated Actions: The Problem of Human-Machine Communication.* Cambridge University Press.

[24] Tomasello, M. 1999. *The Cultural Origins of Human Cognition.* Harvard University Press, Cambridge.

[25] Wu, C. A., Robinson, S. J., and Mazalek, A. 2007. WikiTUI: leaving digital traces in physical books. In *Proceedings of the international Conference on Advances in Computer Entertainment Technology* (Salzburg, Austria, June 13 - 15, 2007). ACE '07, vol. 203. ACM, New York, NY, 264-265.

[26] Wyche, S., Sengers, P., Grinter, R. 2006. Historical Analysis: Using the past to design the future. In *Proceedings of the 8th International Conference on Ubiquitous Computing* (Orange County, CA, USA, September 17 - 21, 2006). Ubicomp '06. ACM, New York, NY, 31-51.