Ubiquitous Computing in Science and Engineering Research Laboratories: A Case Study from Biomedical Engineering

Nancy J. Nersessian, Elke Kurz-Milcke, Jim Davies

1. Introduction

Ubiquitous computing is many visions and applications of information technology to everyday life and work environments. The late Mark Weiser, chief technologist at Xerox PARC and one of the foremost visionaries of ubiquitous computing, formulated as the highest ideal of future developments in computing "to make a computer so imbedded, so fitting, so natural, that we use it without even thinking about it" (Weiser, 2003). This ideal stands opposite the "'dramatic' machine," which in Weiser's words, "is to make a computer so exciting, so wonderful, so interesting, that we never want to be without it".

Ubiquitous computing as a research program in computer science and industry, has led to a number of developments in computer technology, reaching from smart houses to wearable computing devices (Abowd and Mynatt, 2000). This paper will examine ubiquitous computing in the context of science and engineering research laboratories. Ubiquitous computing in this context is both vision and reality. In the first section of this paper we describe three kinds of ubiquitous computing, as they relate to biological and bioengineering laboratories: historically evolved ubiquitous computing, ubiquitous computing by design, and the extreme version of ubiquitous computing by design, *in silico* biology.

The extreme version of ubiquitous computing is not so much concerned with providing a service to researchers in the biosciences laboratory who perform research using *in vivo* and *in vitro* procedures, but rather seeks to move entire branches of biological research *in silico*. In this vision, the dramatic machine reigns. The laboratory is replaced by the computer. To some extent, this is already occurring in research relating to the *Human Genome Project*. One of the most ambitious visions within this movement is the *Digital Human Project*, which has as it goal a "fully functional model of an entire human body from intercellular through tissue level through the organ level right up to the functioning of the entire body" (Shankar Sastry, former head of DARPA's information technology office, as quoted in Taubes, 2002: 70). This vision leads away from the bio-scientists' "wet" work environment to a "dry" environment, where all manipulations are performed with information processing technology. Of course, this vision of ubiquitous computing could not have been initiated, nor can be sustained, without extensive knowledge about biological systems - cells, simple and complex organisms - that continues to be acquired through "wet" experimental research.

A second kind of ubiquitous computing - *by design* - is part vision and part reality. It is exemplified by *The Labscape Project,* which is being carried out by researchers at the University of Washington, supported by Intel. This approach conducts ethnographic studies of the practices of laboratory researchers and aims to develop a ubiquitous computing environment to assist them in these practices. The *Labscape* researchers envision a ubiquitous computing platform for the cell biology laboratory, or in anthropomorphic terms, a "ubiquitous laboratory assistant" (Arnstein, Hung, Franza, Zhou, Borriello, Consolvo, and Su, 2002: 14). This project starts out from the assessment that "most biologists split their time between the physical lab environment and an often remote traditional office environment". In the project designers' view, this situation is "leading to inefficiency and lost opportunity" because documentation of research activity is after the fact, incomplete, often lacking, and not readily available or sharable among lab members. As designers, the Labscape researchers' goal is "to simplify the biologist's life" (Arnstein, L.F. Sigurdsson, S., and Borriello, G., 2001. See also Arnstein, et al., 2002). Consequently, these researchers put much emphasis on the "the development of [a] computer interaction model", in other words, on the interface between experimenter and experiment capture system. In a way, with its emphasis on data collection, storage, and accessibility, the vision of the Labscape project realizes a vision that was articulated in 1945 by Vannevar Bush in his often referenced paper "As we may think". There, Bush (1945: 8) envisioned "the future investigator in his laboratory" supported by mechanized capture of his activity, commentary and observations:

> His hands free, and he is not anchored. As he moves about and observes, he photographs and comments. Time is automatically recorded to tie the two records together. If he goes into the field, he may be connected by radio to his recorder. As he ponders over his notes in the evening, he again talks his comments into the recorder. His typed record, as well as his photographs, may both be in miniature, so that he projects them for examination.

Clearly, Bush wished for an effective and natural capture system, only, despite being a scientist himself, sold the scientists' activity a bit short.

In the development of their interaction model, the *Labscape* designers have recognized two directions that could be taken with their approach to ubiquitous computing: (1) "telemetry-based" capture of activity in the laboratory, meaning that "everything [the plastic ware, the hand tools, instrumentation, the work surfaces] is active" and capable of supporting experimental capture by reporting physical data to the platform, or (2) "full automation of sample handling" (Arnstein, et al. 2001). Whereas the telemetry-based vision would basically preserve the present-day outlook of a cell biology laboratory, the vision of full automation would entail a radical change in this environment: "in this view the physical environment is automated to the degree that all experiments can be performed from the traditional desktop computing environment". From the sources that were available to us about the project, we determine a bias toward the telemetric capture of the lab environment as opposed to fully automated control of lab procedures. This bias is not surprising given that the *Labscape* designers are in a position in which they have to develop their experimental capture systems with fully functional, active research laboratories that maintain and advance existing laboratory practices and procedures. The *Labscape* designers also report that they have chosen to focus on those lab procedures that occur repeatedly in the laboratory. They found that new procedures are exceedingly rare in the laboratory they are working in; and that the input interfaces that were necessary for a system that encountered such procedures "as though it was the first time anything like it had ever been performed in that lab before" were so complex that they rendered the system unusable (Arnstein et al., 2001).

However, research laboratories are often sites of innovation in procedures and technology to carry out experimentation. This is especially the case for biomedical engineering laboratories. For such sites, the truly useful "ubiquitous lab assistant," would need to be capable of adapting to change. When we asked the lab manager of a highly-innovative biomedical engineering laboratory what he thought of the *Labscape* vision, he saw little use for it, as envisioned, in his environment. Still, in the biomedical engineering labs we are studying most of the technological artifacts and many of the procedures are somehow connected to information technology; that is, to a computer that performs some of its functions, either in operating it or in providing particular kinds of output to the scientists, or that analyzes its output. In this sense, ubiquitous computing is already a reality in the present-day biomedical engineering laboratory. As one of the lab members (A7) in the tissue engineering lab we study put it: "we use computers all day every day". In such research environments, many computers are imbedded - as almost invisible, though essential, partners in the lab. Here the imbedding is part of an ongoing process in these labs that we characterize as *historically evolved* ubiquitous computing.

For instance, as we will discuss in *Section 4*, in one of these labs a graduate student constructed a mechanical testing device as part of his Ph.D. research project. Both it and the procedures surrounding it are intensive with information processing technology. This "home-made" mechanical tester has become *the* mechanical testing device in the lab. However, a couple of months ago a commercially built mechanical tester was ordered, with commercially-designed software that will allow, among other things, for testing with larger forces.

Our observations and analysis of biomedical engineering laboratories support Weiser *et al.*'s vision of ubiquitous and invisible computing as already a fact in these environments. These environments are not enamored by the dramatic machine, although certainly the sciences and engineering know their dramatic machines, computers included, and at times have been deeply in love with them. In our paper we are after a different theme; one that, on the surface of it, is less dramatic, less visible, less exhibitive of the extraordinary and yet essential. In this chapter we present our analyses of two procedures, and their associated computing technology, as practiced in a biomedical engineering laboratory. We first discuss our characterization and analysis of the lab as an *evolving distributed cognitive system*, and then present cases of the role of information processing within it (See also Nersessian, et al. 2002; Nersessian *et al.*, in press 2003; Nersessian, in press).

2. The BME research laboratory as an evolving distributed cognitive system

We have several interrelated objectives in our study of biomedical engineering (BME) laboratories, chief among them, developing a cognitive model of the reasoning and representational practices in this *interdiscipline*. Understanding the nature and role of various information processing technologies in creating knowledge has become part of this objective.

We characterize the reasoning and problem solving in the labs we study as *distributed* and *situated*. We are looking at the *cognitive systems* comprising one or more researcher and the *cognitive artifacts* involved in a problem-solving episode; where 'cognitive systems' are understood to be "socio-technical" in nature (Hutchins, 1995) and 'cognitive artifacts' are material media possessing the cognitive properties of being, generating, or manipulating representations. On this model, which for simplicity here we will refer to as 'distributed cognition', the cognition "refers not only to universal patterns of information that transpire inside individuals but also to transformations, the forms and functions of which are shared among individuals, social institutions, and historically accumulated artifacts (tools and concepts)" (Resnick, Levine, and Teasley, 1991).

We are using a distributed cognition model as a framework for analyzing the nature of the representations in the system and the processes that operate on these in the knowledge-making activities in the lab. However, we find in thinking about cognition as it functions in this lab that none of the current conceptions of distributed cognition in the literature are adequate, in that they fail to provide for systems that are evolving over time. In studies of cognition in work environments, for instance, the cockpit or on board a ship, it is often the case that the situations change over time. The problems faced by a pilot change as she is in the process of landing a plane or bringing a ship into the harbor, but the nature of the technology and knowledge of the crew are relatively stable. The cognitive system is dynamic yet largely *synchronic*. To understand cognition in the BME laboratory requires seeing that the situation is dynamic and *diachronic*. This cognitive system undergoes progressive change. The technology and researchers have evolutionary trajectories that must be factored into the understanding of the cognition at any point in time. Our analysis of the cognitive systems in the lab as *evolving* adds a novel dimension to the literature on distributed cognition, which by and large has not examined these kinds of innovative systems. We analyze both the lab in its entirety and the various problem-solving episodes that take place within it as evolving distributed cognitive systems.

To carry out an in-depth analysis of this type of system has required a "mixed-method" approach. We have been conducting both ethnographical studies of the day-to-day practices and cognitive-historical analysis of the problems, artifacts, and models employed in research. We find the mixed-methodology approach essential to investigating cognition and learning in this kind of environment. Cognitive-historical analysis (Nersessian 1992; 1995) allows us to examine the historical development of the components of the cognitive system on multiple levels, including their physical shaping and re-shaping in response to problems, their changing contribution to the models that are developed in the lab at any particular time, and the concepts that dominate the research activity. The ethnographic analysis allows us to investigate the nature and function of the technology as it lives in the laboratory, including its distribution within the lab, the organization of workspace, and the social organization of the lab. The dimension we focus on here is the evolution of some of the information processing technology in the environment.

Lab A, from which we draw the case studies discussed in this paper, applies engineering principles and methods to the study of living cells and tissues for the eventual development of artificial blood vessels. The lab members all come from a predominantly engineering background. Biological knowledge is embedded in the artifacts they construct and in the model-based reasoning they employ in the course of research. An *in vivo/in vitro* division provides a significant part of the cognitive framework guiding practice in the lab. *In vitro* research here starts with culturing of blood vessel cells; in the case of Lab A these are smooth muscle cells and endothelial cells. These are then stimulated and manipulated in various ways to create specific kinds of information. When used as systems for the human body, the biological substitutes must replicate the functions and withstand the environment of the tissues being replaced. This means that the materials used to "grow" these substitutes must coalesce in a way that mimics the properties of native tissues. It also means that the cells that are embedded in the scaffolding material must replicate the capabilities and behaviors of native cells so that the higher level tissue functions can be achieved.

In bioengineering, generally, and in Lab A in particular, technology is continually under development. The technological artifacts in use in Lab A can be sort-ed into *devices*, which are engineered facsimiles that serve as *in-vitro* models; *instruments*, which extract and process information, generate measured output, and enable simulative manipulation, and *equipment*, which assists with manual or mental labor (See *Figure 1*). Instruments can be purchased, made in-house, or a combination of these, such as the mechanical tester we will be examining in *Section 4*. Devices are constructed and modified in the course of research with respect to problems encountered and changes in understanding. Studying the devices underscores how the kinds of systems we are investigating diverge from those investigated by Hutchins. The devices are not stable technological artifacts, but have a history within the research of the lab. For example, as listed in *Figure 1*, the flow loop was first created in the research of the PI of this lab to simulate "known fluid mechanically imposed wall sheer stress," in other words to perform as a model of hemodynamics (See *Figure 2*).[1] We have traced aspects of its development since 1985. The constructs (tubular cell-seeded vascular grafts) were first devised in this lab in 1996 as an important step in the overall objective of creating vascular substitutes for implantation. They afford experimentation not only on cells, but also on structures more closely related to the *in vivo* model. The bioreactor, though having a longer and more varied history outside the lab, first made its appearance in this lab in conjunction with the tubular constructs and was not used anywhere before for that purpose. The current smooth muscle constructs are not strong enough to withstand the mechanical forces in the human (or animal) cardiovascular system. The bioreactor is used to stimulate the cells mechanically with the objective of changing their mechanical properties. The equi-biaxial strain, which simulates blood vessel expansion and contraction, is the newest device modified specifically for this lab, and is just starting to be used as will be discussed in *Section 3*.

ONTOLOGY OF ARTIFACTS

DEVICES	INSTRUMENTS	EQUIPMENT
flow loop	confocal	pipette
bioreactor	flow cytometer	flask
bi-axial strain	mechanical tester	water bath
construct	coulter counter	refrigerator
	"beauty and beast"	sterile hood
	LSM 5 (program)	camera
	computer	

Figure 1: Sorting of lab artifacts by the lab members

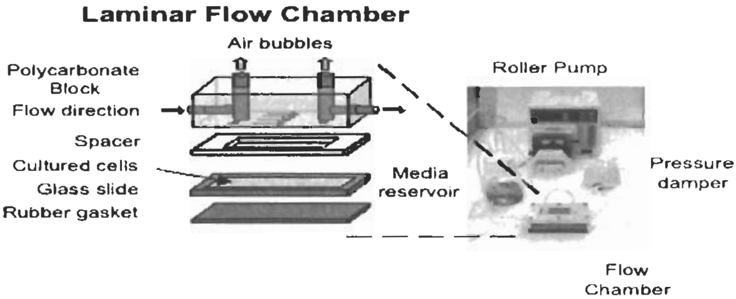

Figure 2: Diagram and photograph of a flow loop (Reprinted by permission of the author of the Ph.D. thesis in which the figure appeared)

The devices are facsimiles (representations) of the arterial environment where experiments can occur at each of the levels identified. These technological facsimiles are locally constructed *in vitro* sites of experimentation. The researchers in the lab call the process of conducting experiments with devices "putting a thought into the bench top and seeing whether it works or not." These instantiated "thoughts" allow simulations of a controlled *in vivo* context, such as the artery, that are constructed to approximate the local forces at work. Within the cognitive systems of the lab, devices instantiate part of the current mental model of the cardiovascular system and allow simulation and manipulation. In this context, we understand a *mental model* to comprise both what are customarily held to be the *internal* thought of the human agent and the *external* device. Understood in this way, simulating the mental model involves the processing of information both in memory and in the environment (See Greeno (1989) for a similar view).

Determining the cognitive artifacts within any cognitive system involves issues of agency and intention that are pressing questions for cognitive science research, both in the development of the theoretical foundations of distributed cognition and in relation to a specific case study. In our analysis, not all parts of the cognitive system are equal. Only the researchers have agency and intentions, which enable the cognitive activities of specific artifacts. The intent of the simulations is to create new situations that parallel *in vivo* situations. It is in relation to the researcher's intent of performing a simulation with the device in order to create new situations that parallel selected dimensions of potential real-world situations, and the activity of the device in so doing, that qualifies a device as a cognitive artifact within the system. For example, as a device, the flow loop (*Figure*

2) process *represents* blood flow in the artery. In the process of simulation, it *manipulates* constructs, which are *representations* of blood vessel walls. After being *manipulated*, the constructs are then removed and examined with the aid of instruments, such as the confocal microscope, which *generates* images for many color channels, at multiple locations, magnifications, and gains. These *manipulations* enable the researchers to determine specific things, such as the number of endothelial cells and whether the filaments align with the direction of flow, or to simply explore the output, just "looking for stuff." Thus, the *representations generated* by the flow loop *manipulations* of the constructs are *propagated* within the cognitive system.

Devices perform as models instantiating current understanding of properties and behaviors of biological systems. For example, the flow loop is constructed so that the behavior of the fluid is such as to create the kinds of mechanical stresses experienced in the vascular system. But devices are also systems themselves; possessing engineering constraints that often require simplification and idealization in instantiating the biological system they are modeling. The flow loop, for instance, is "a first-order approximation of a blood vessel environment ... as the blood flows over the lumen, the endothelial cells experience a shear stress. ... we try to emulate that environment. But we also try to eliminate as many extraneous variables as possible". (A10) So, as with all models, devices are idealizations.

A significant part of creating artificial blood vessels is to get them to be able to withstand the mechanical forces associated with blood flow though the vessels *in vivo*. The first steps in making artificial blood vessels are to culture cells, create constructs, and stimulate them in devices that model certain aspects of the current understanding of flow processes in an effort to improve them, e.g., making them stronger or making them proliferate. Information is extracted from the stimulated cells and processed by instruments that employ information processing technology to provide measured outputs of various kinds, in the form of histograms, dot plots, and other visual representations. These analyses most often pertain to stress/strain, such as measures of elasticity (linear modulus), shear stress, ultimate tensile stress (maximum stress a construct can withstand), toughness (measure of the amount of energy it take to break the construct), and to cell volume, or health of the cells (alive/dead ratio), under mechanical stimulation and proliferation.

All the devices and instruments can be categorized as cognitive artifacts in that they generate, manipulate, and propagate representations within the cognitive systems of the lab. All devices and instruments have computers and programs associated with them - either directly in their use or indirectly in that the information created by them is extracted and processed by these. We take as our case studies one device and one instrument. As we will see, the device case study establishes that even in the instances where a cognitive artifact, such as the *equi-*

biaxial strain device, is free of information processing technology, in the problem-solving process it participates in a cognitive system where computing is ubiquitous. The case study of the instrument, the *mechanical tester*, affords an opportunity to bring to the fore information processing technology largely invisible to – or rendered invisible by - the researchers, as well as to document the historical dimension of its evolution within this lab.

3. Case study: The equi-biaxial strain device

Exploring the mechanical effects on cells, the laboratory constantly subjects cells to stretching. Sometimes, as in the case of the mechanical tester, cell constructs are stretched in order to measure their strength. However constructs are also stretched to condition them and change their properties. The EBASD, or equi-biaxial strain device is free of information technology: it has a only a single cord, for power, coming from it (See *Figure 3*). It is a metal object with a motor, an apparent relic from an industrial age, seeming out of place amidst so many computers. It stimulates cells by stretching "jello-like" constructs once per second for an entire day. The problem solving it participates in, is the labs' constant attempt to make arterial substitutes strong enough to withstand the forces within the *in vivo* system, human or animal.

Figure 3: Equibiaxial Strain Device (EBASD) with four membrane holder rings. The device is placed in an incubator during operation.

Most researchers in Lab A are interested in blood vessels. A10 is unique in that he wants to understand the heart and the cells that make up its valves. One thing that makes the valvular cells different from others is that, due to the pumping, they experience great stretching. A10 thinks that this stretching might somehow strengthen groups of cells. Wanting to test this experimentally, he could not find what he needed among the devices already in the lab. The only device that does repeated stretching is the bioreactor, which pumps liquid into a section of a tubular cell construct again and again. But A10's mechanical engineering background makes him a stickler for control. In the bioreactor different parts of the construct were experiencing different stretches:

> ...the ends of the thing are very rigid, and you suture the construct, or whatever, on it. Well, in the middle it's going to pulse the most. And on the end it's not going to pulse as much...If you're really trying to look at cellular behavior, I think you— I think it's critical to make sure that you're doing the same things to every single cell.

He found the control he was looking for in the EBASD, created by the prolific San Diego inventor we will call Dr. Y. This device was constructed to stretch a membrane in all directions at once. Cells stuck to the membrane each experience the same exact stretching effect. So, using this, A10 would know that all the cells were reacting to the same effect. He secured funding to get one of his own and flew to San Diego to consult with Dr. Y.

Devices like this undergo improvements with each one built, and the machine A10 got was different - "tweaked" with improvements since the version A10 read about in the original paper: holes were drilled to accommodate long screws (adjusting the screws changes the amount of strain), the bearings were re-adjusted to make the surface go straight up and down, and the o-ring groove was re-cut because it was too small to push the O-ring in. These changes were practical, having to do with the functioning of the device, and were not made with the *in vivo* model of valve stretching in mind. A10 was there, working with Dr. Y's laboratory, calibrating the device and using his mechanical engineering background to make sure it was working correctly.

Back in A10's lab, the EBASD now resides in a large incubator so the cells do not get contaminated. The metal machine is varnished brightly so that the humidity inside will not cause it to rust. The EBASD, as depicted in *Figure 4*, has a mobile metal plate with a hole in it. Stretched across the hole is a rubber sheet with cells stuck to it. The Plate moves up and down, stretching the membrane, and the cells with it, over the indenter ring, a hollow metal cylinder. Pulled over this ring, the cells are stretched on the rubber sheet. The whole EBASD has four of these holes, membranes, and indenter rings, allowing four simultaneous experiments. With this machine, specific experiments can be conducted, for instance, in one experiment this happens over and over, about one time per second, for 24 hours. In this way the EBASD conditions cells with biaxial strain.

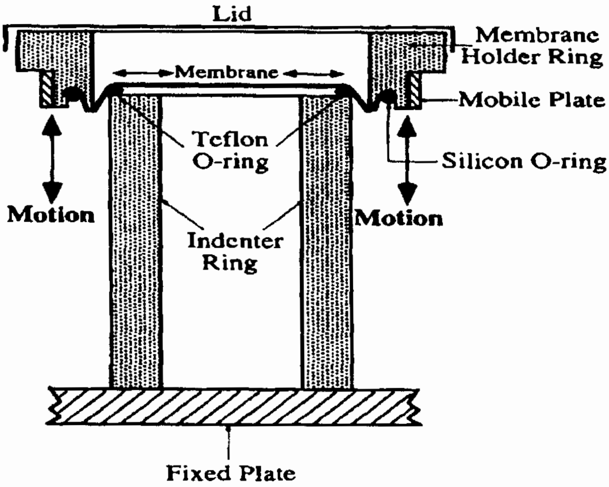

Figure 4: Cross-sectional view of one of the hollow cylinders with a Teflon O-ring on top of it used with the Equibiaxial Strain Device (EBASD). A membrane holder ring is fixed on a mobile plate, which is driven to move vertically up and down. As the mobile plate moves downward, it stretches the membrane by pulling down the periphery of the membrane around the Teflon O-ring. (Reprinted with permission from the Biomedical Engineering Society.)

The EBASD is a completely analog machine free of information technology - it isn't even attached to a timer. There are no wires from the EBASD to any other machine. The device instantiates part of the researcher's current mental model of blood/heart vessel expansion. Within the cognitive system, it manipulates valvular cell constructs, which are representations of cells *in vivo,* providing information that is then propagated in the system through analysis with instruments. During our first interview with A10, he had not even thought through how to analyze the cells that the machine conditioned.

> ...there's some kits that you can use to make those kinds of assays. So I haven't exactly looked into that yet because I'm so far away from worrying about that I just do this other stuff.

But once the cells are conditioned, they must be analyzed. The EBASD is not a measurement tool. A10 is interested in knowing whether the cells have gotten stronger. The strength cannot be measured directly, so he has to

> get them off the membrane, and then eat them up, like lyse them, and then take that, and do a test for, like I want to see what kinds and how much extracellular matrix they're producing.

What A10 means by "lyse them" is to put a digesting agent on the cells so they will get off the rubber sheet. He cares about this "extracellular matrix" because

> the cells secrete these proteins out um, I surmise that the valvular cells because they're in a highly dynamic flexing environment that's at a frequency, and that they have to constantly remodel the matrix they're in, to kind of repair it.

His line of reasoning is, then, that one part of a valve gaining strength involves producing proteins, so if he can find that stretched cells produce more protein then non-stretched cells, it supports his hypothesis that stretching makes cells react by strengthening.

A few months later we interviewed A10 again, and he had figured out how to measure protein generation. The whole process of getting data from the results of the EBASD is quite complex, involving several steps:

1. Isolating RNA from the experimental cells.
2. Putting those RNAs on a gene microarray.
3. Generating an image from the gene microarray.
4. Analyzing of the image for fluorescent intensity.
5. Statistically analyzing the intensity.

Rather than measuring protein output directly, he uses gene microarrays. A gene microarray is a small object with thousands of little piles of nucleotides "spotted" upon it. Each of these nucleotides reacts to the RNA of a certain kind of gene. The RNA is isolated from the experimental cells and then set to react on the microarray. When they react, they emit a fluorescent dye. The intensity indicates the amount of RNA that is reacting. The nucleotides are spatially organized. That is, where the fluorescence comes from on the array indicates what kind of RNA is reacting.

The companies that create gene microarrays provide software that helps to find out what is fluorescing where. Here, then, the information technology, so pervasive in the lab, starts to become apparent even with the EBASD device experiments. A special machine uses lasers to make a "very high resolution image" of the array. This image is analyzed by software to determine which nucleotides fluoresced, and how much. This part of the analysis is actually done by an expert at a neighboring college, where the machine resides. The numerical outputs of this software are then analyzed with a statistical software package. The genes are assumed to correlate with protein production:

> The assumption is that ... copies of genes, especially the messenger RNA which is what we're really looking at, uh, and amount of protein are going to be proportional...Three times as many gene copies will be three times as many—as much of that protein. So. But it is an assumption, it very well may not hold.

A10 is interested, primarily, in how valvular cells react to stretching differently than do other cells. Strengthening is one way they could interact: "...there may be characteristics from the gene profile that suggest that they will interact with the matrix in a certain way that may strengthen...". So in actuality the measurement is quite indirect. The experimenter runs statistics on numbers generated by software that looks at light intensity on an image taken from a microarray filled with reacting RNA on nucleotides, which are there to make proteins. Proteins are made to make cell populations stronger; which is what the experimenter, and indeed the whole lab, is interested in. So conditioned cells - the manipulated representations produced by the EBASD - not wires, weave the thread from the motor-controlled device to computers. Though the EBASD itself does not involve information technology, computers and software are absolutely essential for the analysis of what the EBASD does to its cells, reinforcing the ubiquity and necessity of computing in the research of the modern biomedical engineering laboratory.

4. Case study: The mechanical tester

As we have said, the research in Lab A seeks to develop artificial, cell-seeded vascular grafts for eventual implantation into the human body. Thus, this biomedical engineering laboratory cultures various types of cells associated with the mammalian cardiovascular system, such as smooth muscle cells, endothelial cells (the cells lining the inner most wall of the vascular system), cells specific to the heart valves, and even embryonic stem cells derived from mice. These cell types are derived from various mammalian species, among them, rats, dogs, pigs, and humans. They then create various cell-seeded artifacts that incorporate a number of materials and components. Here we focus on a testing procedure for the tubular-shaped, bio-engineered cell-seeded vascular grafts, locally referred to simply as '*constructs*'. The design of the constructs is continuously under revision, as new projects are developed to further the lab's general research agenda. Most importantly, however, the properties of the various designs need to be evaluated as new design possibilities emerge out of the ongoing research. Construct design and construct evaluation, thus, go hand in hand in the lab's overall research agenda, but the problem solving varies in type and focus for the various projects that are carried out by the individual lab members.

For this case study we focus on a particular testing procedure that seeks out the mechanical properties of the cell-seeded constructs developed in this particular BME laboratory. The instrument is variably called "mechanical testing apparatus" or "ring testing apparatus", and colloquially *the mechanical tester*. Its purpose is to acquire data that allow for an assessment of the mechanical properties of tubular constructs. For this purpose the tubular constructs are sliced into 5mm rings. These rings are subsequently tested one by one with the mechanical tester. Before testing, the specimens are typically exposed to a cyclic preconditioning regiment during which the rings are repeatedly stretched to a lesser degree (e.g. approximately 20% of the strain at failure); the purpose of preconditioning is "to remove stress history". During testing each ring is uniaxially (i.e., in one direction) stretched to failure, until the specimen breaks at one or several points; at a constant strain rate (i.e., moving the lower hook downward at a constant rate, e.g., 0.2mm/sec) (See *Figure 5*). Other test regimens are possible and are implemented as well, e.g., so called creep and stress relaxation tests, which characterize material performance under constant strain or stress conditions). We describe the testing procedure, the related data acquisition and analysis in some more detail in the next sections in which our main emphasis is on two related issues: (1) how the researchers "see" the mechanical tester and (2) how measurement occurs. Both themes contribute to the analysis of the role of information technology as it is integrated into this measurement procedure. Our analysis underscores the ubiquity and invisibility of information technology in this setting.

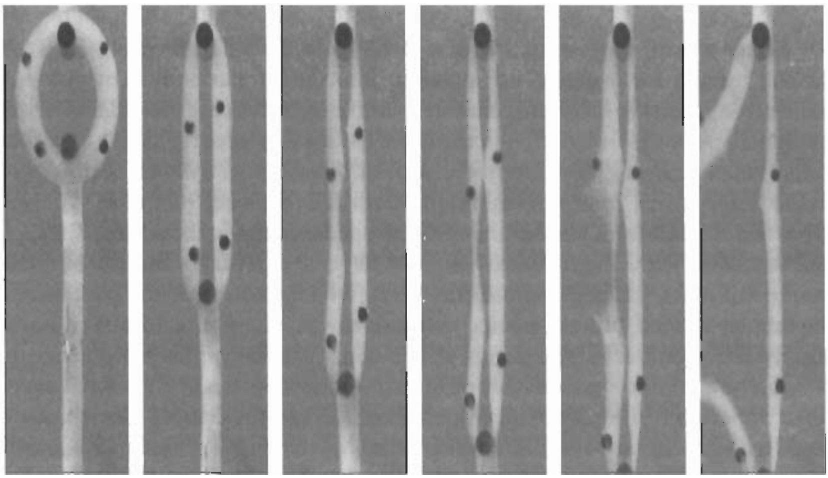

Figure 5: A ring specimen cut from a cell-seeded construct is tested to failure with the Mechanical Tester (MT). The progression is recorded here. The specimen is threaded through two hooks, the lower hook is vertically driven downwards. Also visible are the four beads glued to the ring specimen, the researchers capture the movements of the beads in order to determine strain in a more local fashion. (Reprinted by permission of the author of the Ph.D. thesis in which the figure appeared)

4.1 Let's see!

Figure 6 shows an annotated and illustrated photograph of the mechanical tester as it is included in a lab member's recent Ph.D. thesis. What springs into the eyes is the dark steel frame that contains the apparatus' mechanical machinery including the servo motor that is used to move down a hook in order to stretch the ring specimen. This mostly black steel structure, which seeks to combine sturdiness and precision, contrasts starkly with the translucent "environmental test chamber" holding the artificial/biological specimen. The test chamber is framed by a more delicate appearing structure that holds a load cell, a precision measurement device, above the crystal-like chamber containing the ring specimen mounted on two hooks. In the drawing left of the photograph, which details the test chamber, the hooks appear as lines ending in small circular shapes that in this figure are merged with the "ring test sample". The drawing shows the ring sample slightly stretched to form an oval. Of special importance in this set-up is a CCD camera (a precision digital video camera, seen in the upper right corner of the photograph) mounted in front of the test chamber and used to make a video recording of each ring-stretching test. Highly significant for our argument at this point, however, is what is *not* shown by the photograph; namely, in one phrase, *almost all of the information technology* used with this testing and measurement procedure.

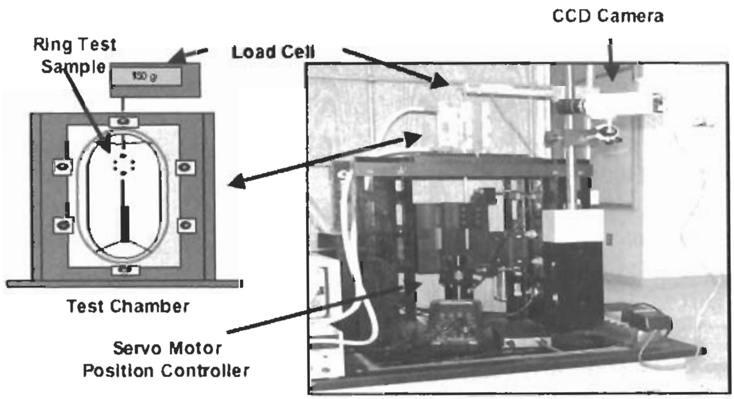

Figure 6: Photograph and schematic of the Mechanical Tester (MT) as shown in a Ph.D. thesis by one of the lab members. The testing instrument consists of five components: the environmental test chamber (see schematic enlargement), the force transducer load cell, the servo motor position controller, the digital video camera and the data acquisition system. Remarkable about this depiction of the MT is how the information technology associated with the MT (apart from the video camera) remains off to the side, invisible. (Reprinted by permission of the author of the Ph.D. thesis in which the figure appeared)

In fact, the perspective on the mechanical tester in this photograph (*Figure 6*) is best suited to give an impression of the mechanical make-up of the mechanical tester. Most of the numerous cables running from and to the electronic parts of the tester are not visible in this particular depiction of the mechanical tester. The electronic parts of the set-up are positioned to the left of (a person standing in front of and facing) the apparatus as shown in the photograph (again, except for the video camera). Moving the picture frame to the left and up we would see a number of electronic devices and cables connecting them, including a Pentium PC, keyboard and monitor (See our photograph, *Figure 7*). Computer and electronic devices are sitting on a workbench immediately adjacent to the short-legged wooden table holding the tester. Some more electronic parts are stacked on shelves above that work bench and some are sitting in that little bit of space that is left beside the steel frame on the wooden table. For a person not intimately familiar with the set-up it is difficult to discern which of the devices sitting on the shelves above the PC are part of the mechanical tester, and which are sitting there for other reasons. Unless one gets an in-depth tutorial on the set-up by an insider (and not everybody in the lab is expert on this mechanical tester) the best advice to be had on how it is put together seems to be that given by one of the lab members: "You just look where the cables go to find out what it does".

Figure 7: Our photo of the Mechanical Tester (MT) seen from a different angle. Grouped to the left (of a person standing in front) is a PC, computer screen, keyboard and mouse. Various components of the MT are connected to the computer through an acquisition board. The acquisition board is used to sample and synchronize force and position data using *LabView* software; in addition, the signal from the load cell transducer is transmitted through an amplifier signal conditioner. The servomotor of the MT receives analog input from the load cell transducer and communicates signal outputs to the PC computer. The CCD camera is connected to the PC computer through another specialized acquisition board, images are collected using the imaging software *Inspector*.

The information technology does a number of things in the case of the mechanical tester, in the most general terms: (1) controls the servo motor that moves the lower hook and thus strains the ring sample, (2) acquires force and displacement data, and (3) stores the videotape that is recorded for each sample testing. Not explicit with this functional description is the interconnectivity of the various parts included in the set-up, for instance, the feedback-loop between the load cell that measures force and the servo motor controller which is mediated through the PC. Running an experiment requires interacting with a number of software programs running on the PC next to the tester itself. The software includes a program that communicates with the servo motor, a program that controls and stores force and position data, a program that is used to synchronize these data into tables for further analysis, a program for the acquisition and storage of images recorded by the video camera. The sense one gets from talking to current lab members about the mechanical tester and its parts is that they feel only partially responsible for the exact set-up and wiring of the testing apparatus. They, in fact, have inherited this set-up from a former Ph.D. student in the lab who developed this mechanical tester in collaboration with a professor at the school of mechanical engineering. That they know how to work the apparatus, though, is evidenced in a number of recent research projects involving the tester, one of them even being carried out by an undergraduate under the supervision of a graduate student in the lab.

Why are the individual tests captured on videotape? The initial, spontaneous answer of a lab member to this question was the following: "Because the person before us did it". He then continued to explain that there are somewhat differing opinions about this aspect of the procedure, but that it was necessary for obtaining data on *local* strain as opposed to the strain that is experienced by the test sample in its entirety. In a nutshell, the displacement data that are collected during a test through the servo motor controller allow the researchers to compute the strain experienced by the ring sample during testing. Strain is a dimensionless concept that relates change in length to original length (thus canceling out the units of measurement). By contrast, *local* strain, in this case, refers to the change in length that the sample experiences during testing in that part of the ring that is most closely parallel to the direction of displacement (that is, not the parts that are bent by the hooks). To track this local change the researchers glue four small beads to each ring sample. *Figure 8* shows a mounted ring sample with two beads glued to the right and two beads glued the left portion of the ring (the beads are glued to places approximately corresponding to the positions of the *2* and the *4* on a clock dial and to the *8* and *10* on the other side).

In order to compute local strain the distance of the beads is measured on screen while replaying and stopping the tape at particular frames of recording. In fact, a closer look at this second stage of data acquisition, which happens during replay of the recorded tests and in combination with the general data analysis, reveals why this part of the procedure is commonly regarded "as such a pain" by the lab members working with the mechanical tester. When one of them demonstrated this procedure to us we counted about 28 transitions between various windows on screen, a protocol sheet, and a hand-held calculator for *each* sample testing. This second stage of data acquisition and subsequent analysis takes place entirely in front of a computer screen. When we witnessed the procedure it took place at a PC on the other end of the lab from tester itself.

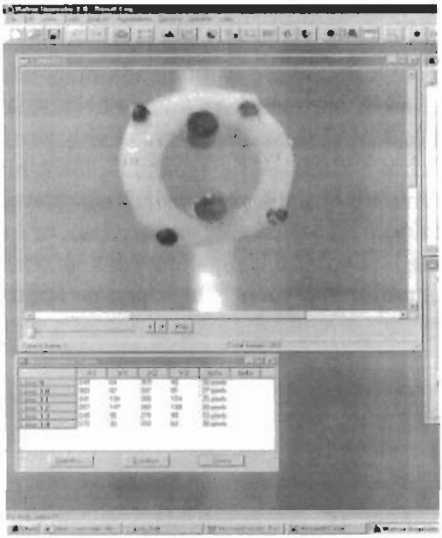

Figure 8: Screen shot of the videotaped capture of a ring specimen mounted on hooks for testing with the Mechanical Tester (MT). Wall-thickness of the specimen is measured on screen at six places with a line tool provided by the *Matrox Inspector* application. The lines for measurement in this particular frame are labeled Line 9-14, and their coordinates and lengths measured in pixels are tabulated in a separate window. The researchers take great care when drawing these lines, if possible taking the shadow around the edge of the two-dimensional depiction of the three-dimensional object into account.

All testing involving any type of mechanical tester is geared towards relating stress and strain. Strain corresponds to distension, a change in length of the material, and is normalized with respect to original length (*See Figure 9*). Stress is force relative to area. The outcome of the testing procedure that concerns us here is the relationship of stress and strain as a characteristic of the material properties of the constructs from which the sample rings are cut. This characteristic is most often represented visually, as a graph with strain on the abscissa and stress on the ordinate. From this relationship a number of additional parameters are determined, numerically and as aspects of the graphical representation, among them are:

-The stress at which the sample begins to break, called the *yield stress*, which shows as a small dent in the graph that rises after this dent to the point of *ultimate stress*.

-The *linear modulus*, which characterizes that part of the curve, in which stress and strain are related linearly (in correspondence with Hooke's law), characteristically drawn next to the respective part of the curve as the hypotenuse of a triangle. In practice, the modulus is either determined computationally from best fit curves of the linear segment(s) of the stress-strain relationship or defined as a region spanning a particular stress range, e.g., 25 to 75% of the ultimate stress experienced by a sample

-The *yield energy*, which is the amount of work required to bring a sample to the point of yielding, and computed by integrating the area underneath the stress-strain curve as it rises from the origin to the point of yielding.

The graphical representation of the stress-strain curve, thus, relates these concepts in a single display and through a multi-step procedure with the actual testing of the ring samples as is captured on videotape. The data are analyzed using *Excel*.

Within the cognitive systems of Lab A, then, the mechanical tester manipulates constructs, which are representations of blood vessels, and partakes in the propagation of information within the system through generating numerical and visual representations.

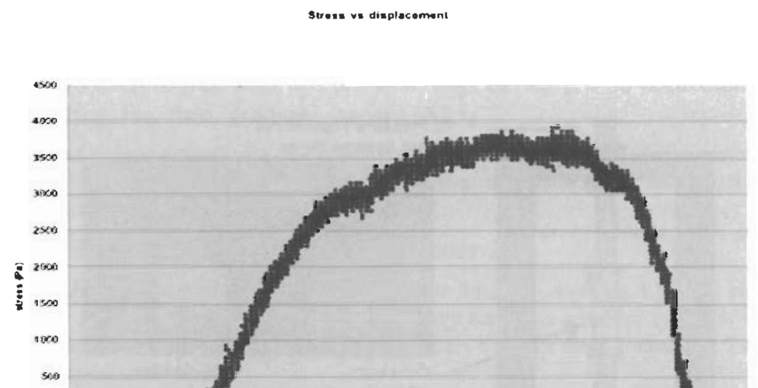

Figure 9: Graph showing a cumulative record of tests of cell-seeded constructs with the Mechanical Tester. Here stress, as the force experienced by the specimen and normalized with respect to area, is graphed against displacement, in this case of the hooks. Displacement, as a change in length, is here normalized with respect to original length, in this case distance of the hooks. The resulting graph shows the typical material characteristics of the cell-seeded constructs, after an initial tail region, stress increases linearly with displacement (strain) leveling off and dipping after yielding and failure.

4.2 Historically evolved mechanical testing
Biomedical engineers seek to build devices and instruments to expose their specimen to conditions that emulate aspects of biological environments and they then seek to measure the effects of these conditions on their specimen. In general, this approach entails a dual emphasis on measurement and quantification: (1) The environmental conditions, to which the specimens are exposed by the devices and instruments, are ideally well understood in terms of models with variables and parameters of which at least some can be manipulated and/or measured, and (2) the effects of the exposure on the specimen are measured by an instrument, in fact, most often a multi-instrument procedure. With the artificial blood vessels, the tubular *constructs*, one of the immediate questions has been how their strength compares to native vessels. This question obviously entails the question of how strong native vessels are. The story of the mechanical tester and testing procedure that we have encountered in this laboratory fits these questions into the development of one particular instrument, the mechanical tester currently in use in this laboratory (*Figures 6 and 7*).

Prior to the development of the mechanical tester, crude measures of construct strength were generated using the *Burst Test Apparatus* (See, *Figure 10*). In this testing procedure, the entire tubular construct was sutured onto the test apparatus and filled with saline via a syringe pump until it ruptured. Pressures were recorded using a catheter-type transducer and diameters were captured with the CCD camera. So, information processing technology was used in data recording, but not generation, and in a limited form of strength analysis.

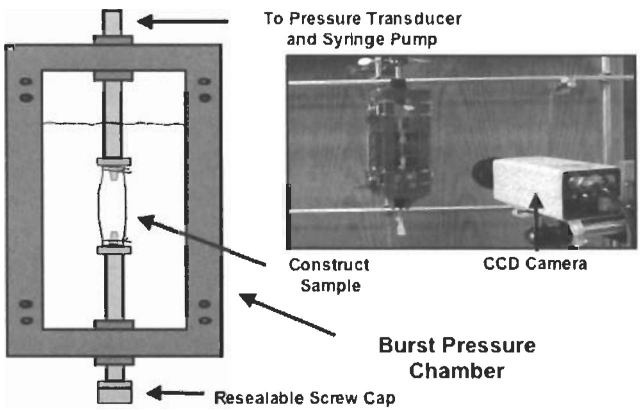

Figure 10: Illustration of the Burst Testing Apparatus. Tubular constructs were loaded into the burst pressure chamber and sutured onto lure pegs. After the chamber was filled with saline and sealed, the constructs were filled with saline via a syringe pump until they ruptured. A catheter-type transducer recorded the pressures while construct diameters were captured using a CCD camera. (Reprinted by permission of the author of the Ph.D. thesis in which the figure appeared)

Years before this mechanical tester was ready to pose for a photograph to be incorporated into a doctoral dissertation, it sat in a corner of another biomedical engineering laboratory as a "big black thing," completely unused at the time, "almost ready to be gone for salvage" (quotes by former graduate student A23). In the recollection of the graduate student (A23) who took the initiative to remobilize the device, whenever he went down the hall to the other lab he saw "this awfully old and clut-, clumpy, sort of, not clumpy but, you know uhm sort of awkward looking device". He told us that he recognized the device as a "ring tester", which "was sort of in pieces". The laboratory that housed the device was focused on the mechanical study of living, native tissue and had used the device to test native vessels. When the graduate student "borrowed" it, moving it down to his lab, "it only had the reservoir and the frame, nothing else but that". Borrowing a "clumpy" device and putting it back to use required the consent and support of the two PIs. This was not a problem in this case, as one was happy to lend it and the other was willing to have "7000 dollars, or I don't think it's 7000, something like 5000 dollars" spent to

> make a testing device that was able to test things with very high sensitivity for the sort of uh [pause] tissue that we were growing which was, ya, two orders of magnitude lower mechanical strength than the native tissue.

With only the reservoir for holding and stretching the specimen and a steel frame the device was not yet much of a mechanical tester when it was brought to its new home down the hall. (Incidentally, to this day the tester has remained in this lab and has even moved with this lab to another building.). So immediately after its relocation, the, then, graduate student (A23)

> started ordering the device, the peripheral equipment that was needed, computer, uhm linear position table, uhm force transducer, uhm motor, and assembled the entire thing together.

Still with a hint of pride, he told us in this interview:

> But uh, you know, in a few months this whole thing was working, I had the computer controlling the motor, so I was able to tell the motor where to go which was the first step. Uh I had the computer taking data from the force transducer; I was able to measure forces.

However, the worst part was still to come. What was still missing from the device was a good way of

> measuring strain, measuring how much the material would distend. The displacement of the hooks was one way of doing it but it was not a very accurate way. Because if you had inhomogeneities in the wall, the hook's displacement didn't necessarily correlate well to the displacement of the tissue, of the wall tissue.

Not satisfied with this crude measure of strain he thought of a way to measure local distension of the specimen:

> And so what I did was actually start putting small beads, black dots on the tissue and video it, video it, uh, video recording uh those small beads as the tissue distended. And what that enabled me to do was to measure on the tissue how much those beads would displace to get a true measurement of the strain of the sample.

The difficulty with setting up the computational routines for this measurement procedure - and subsequently for others with learning the procedure - was the orchestration of the multiple measurements that this involved and that eventually would contribute to the graphical representation of the stress-strain curve. In the originator's words (A23) the procedure was "very labor intensive" involving the programming, use, and adjustment of a number of macros with the video analysis software *Matrox Inspector* and the spreadsheet-based analysis software *Excel.* When he described the procedure, his description centered on what he considered the procedure's ultimate purpose (emphasis added):

> 'Cause it was getting a video signal, it was getting a, 'cause all this video was digitized, it was getting an input from the force transducer, and one had to correlate the force transducer input with the video signal input, in order to, *I mean what you ultimately want to end up with is force on one axes and displacement on the other axes*. Now this is a video signal, ok, and this is a voltage, voltage from uh force transducer [drawing and labeling a graph]. So the difficulty is here, we are trying to correlate those two things.

We were given a very different account from this narrative by the originator of the procedure, when we interviewed an undergraduate student (A27) who used the mechanical tester in a research project that she was carrying out in a year-long internship with the lab. At the time of her internship, of course, the student who had built and instituted the procedure was long gone (only making occasional visits to the lab from overseas). The student demonstrated the procedure to us during an extended interview. At the beginning of her run through the procedure and after many mouse clicks opening the Matrox Inspector software, selecting and opening a video file, and the Matrox Inspector macros she said:

> Well, let's see. [turns away to grab something out of a folder] There is a lot of different things that go into it [laughs]. But basically I have a sheet that I follow.

The analysis protocol, as the sheet was labeled, had a header with three slots—*Experiment*, *Construct*, *Date*—and about thirty additional slots interspersed throughout the sheet. All of these were filled with numbers as she went through this measurement and analysis procedure. Some of these numbers represented measurements, some frame numbers specifying salient moments in a test run (e.g., the frame number corresponding to *LHP + F25%,* which corresponds to a displacement of the lower hook at 25% of the ultimate force), and some the results of calculations, either carried out using a hand-held calculator or by running a software macro. The protocol was divided by headers such as "*Run Force Displacement Macro, In Matrox:*", or "*Run Beadfinder Macro in Matrox (change frame # and min/max area)*" and the slots were labeled, for instance, *F75%*

:[slot], or *SigmaMax=[slot]*, or they marked parts of equations such as *[slot]mm*[slot]pix/mm=[slot]pix]*. When we observed her during the analysis procedure we noted the constant back and forth between various windows on screen, the analysis protocol, and a hand-held calculator. We also observed how the interaction with the protocol required her to make occasional jumps when entering a number, breaking the obvious path from working the protocol strictly from top to bottom.

The hand-held calculator came in for two purposes, to compute the average wall thickness, which was measured on-screen at six places on the ring sample, and to convert millimeters into pixels and *vice versa* using a ratio of conversion that she had to establish for each test and record on the protocol sheet. Where on-screen measurement was required she used a line tool provided by the *Matrox* application. In fact, the on-screen measurements of the wall thickness of the circular, not yet distended specimen was carried out with such care as to take the shadows around the edges of the videotaped sample into account. Working her way through the analysis protocol, at various points she had to adjust *Excel* macros for the number of entries used for the specified calculations and also certain values used in these calculations such as the conversion ratio for millimeters and pixels, which depended on the exact camera setting during a test. All in all, a lot of disciplined work, if one is to perform an experiment involving more than eighty constructs, as was done by this undergraduate intern (and that was merely the measurement and data analysis part, not counting in the hours for cell culturing and preparation of constructs).

Observing her carrying out this procedure made it clear to us how much can go wrong. More than once, she had to backtrack, the wrong window had been opened, or the computer responded with sounds going either *plim* or *blum* indicating a complaint: an error of some type had occurred. We ourselves had a hard time following her hastily opening and closing windows and re-doing calculations. In fact, a couple of weeks later we asked her for a second interview to improve our still sketchy understanding of what was going on. We came away from this second interview concluding that the student's understanding of the procedure had improved. She seemed to better understand the concepts of stress and strain and their relationship to the ultimate goal of establishing a stress-strain curve as a description of tissue characteristics. Behind our account of the student's performance lurks the question of what enabled her achievement in terms of the lab's organization and operation. Obviously, it cannot be enough to hand the student the analysis protocol and to allow access to computer and software. This student faced the task of following an established procedure with many arbitrary decisions built into it, for instance, the labeling and organization of the macros, or the decision to determine the modulus of elasticity (the "linear portion" of the curve) between 25 and 75% of the ultimate force. In fact, this particular decision had been introduced to the procedure by another graduate student

(A11) in his dissertation project, which was heavily involved with the mechanical tester. (By contrast, A23 had approximated the linear portion of each curve by a computational criterion). In order for a student to learn this analysis procedure then, what are required are lab members who are familiar enough with the device and the procedure to apprentice her or him, at least to some extent.

In the case of this mechanical tester, we can easily draw such a line of descent, reaching from the student who brought the device to the lab (A23) to the undergraduate (A27) who received the device and procedure ready-made. For this case, the handing-down involves only two other graduate students: A11 who worked with the mechanical tester for his dissertation and whose time in the lab overlapped with that of A23 and with that of the undergraduate intern and especially with that of the undergraduate's student mentor, graduate student A7. Although, as very advanced graduate student, A11 did not spend as much time in the lab as he used to, he still served as an important repository of skill and knowledge on the mechanical tester for these students, undergraduate and graduate mentor.

A couple of years and many, many tests later, the laboratory from which the originator graduated has bought one of the commercially available testers. Graduate student A7 was assigned the task by the PI to coordinate the acquisition and set-up of the "store-bought" mechanical tester. Until very recently, the new store-bought mechanical tester was sitting in boxes in the institute's basement. A7 told us that it has many more "feedback capabilities," including greater control of the force, and will allow for more extensive testing, also with larger forces, which is important because the constructs themselves are now stronger than when the "home-made" instrument was constructed. Additionally, it is capable of a greater variety of testing, especially related to visco-elastic testing of constructs, because

> it also has the control to do um, not just test to failure, but this feedback, which is things like creep and stress relaxation are different kinds of mechanical tests you can do with it easily [A7].

The emphasis in this quote is on "easily," since creep and stress relaxation tests have been carried out with the old mechanical tester but required programming and subsequently adjustment of "motor control profiles", programs that signal the motor to move the linear position table in particular ways. The new mechanical tester comes with software that supports a windows interface and will not require this kind of programming. Although the tester was for the most part still in boxes, A7 had started to take a look at the accompanying software. Despite promises by the commercial provider of compatibility with software in use in the lab, A7 subsequently had several exchanges with the company about compatibility issues.

Recently, the task of setting-up the new mechanical tester has been passed on to a new graduate student (A22) who has very limited hands-on experience with the old mechanical tester. Her current worry is "designing the fixtures" for the new tester, which, as designed by the manufacturer, is a "multipurpose design", "it doesn't have hooks", or for that matter an environmental chamber [A22; field notes 6/25/03]. A22 is especially seeking an ergonomically better design of the environmental chamber, possibly with a front latch. In this way the ring specimen could be mounted more easily on the hooks than with the old design, which had the researchers reach into the chamber from above through a relatively small opening (approximately 3 cm in diameter). By now the new mechanical tester has been taken out of the boxes and the parts are sitting on the bench top in the custom-designed room at the end of the hallway. Instead of one the new mechanical tester will have two computers used with it, one controlling the operation of the tester itself and one for data capture. The IT was bought according to the recommendations of the manufacturer. Computers and the mechanical tester as such were obviously all new and untouched, when we, accompanied by A22, visited the new instrument in its somewhat removed and private location. We did not see a keyboard or a mouse yet with the system and the parts were not connected to each other or even to a power source. According to A22 currently the plan is to also move the old mechanical tester to this location. There is a pragmatic reason, A22 told us that they may want to compare test results from the two testers and thus may need the digital video camera with both, old and new tester.

As with the old mechanical tester, the measurement of local distension of the ring specimen during testing will still require video capture and analysis of individual tests, also with the new mechanical tester. Thus, as long as local distension or strain is taken into account, the new mechanical tester will to some extent inherit the labor-intensive data acquisition and analysis procedure associated with the old mechanical tester. A22 hopes eventually to be able to show that the measurement of local distension is obsolete, by studying its correlation with the overall distension of the specimen, i.e., the distance between the hooks. She thinks that for a while to come the old mechanical tester will be in use, simply because some lab members have learned how to use it. Currently, A7, who is the only remaining graduate student having first-hand experience with the old tester, is teaching the new undergraduates in the lab how to use the instrument. For her degree, A7 is pursuing a different line of research within the lab, not immediately related to the characterization of the cell-seeded constructs using mechanical testing. A22 is also not entirely sure what role the mechanical tester will play in her thesis-related research, but her project is moving away from mechanical testing. She will set up the new tester but it remains an open question who in the near future might be its primary user and eventually lab expert on the new tester.

The fate of the old mechanical tester is not yet fully determined. In the near future it will, most likely, be moved in with the new mechanical tester. If A22 is right, no matter what it will be in use for a while to come, simply because of its familiarity. However, from the manner in which A22 and also A7 described the "user-friendliness" of the new system, and the advantages in terms of flexibility and control during testing, it seems likely that eventually the old mechanical tester will be a fossil again, sitting in a dark corner of the room, and very likely stripped at least of some of its "peripheral equipment," with the latter used elsewhere in the lab. We cannot know for certain but we suspect that this time around, rather than sitting alone, the retired mechanical tester will be accompanied by a test chamber and possibly have some other equipment stored with it, such as the I/O board that was used to collect the force and position data. The graduate student who originally devised the mechanical tester had the casting for the acquisition board jokingly labeled with his initials followed by "Industries Inc." Thus, the new fossil, that is, the old mechanical tester, may even have some remnants of the information technology retired alongside it.

5. Conclusions: Ubiquity and the analog - digital spiral

Ubiquitous computing - not by vision or design, but by historical evolution - is a *fait accompli* in the modern biomedical engineering laboratory. We suspect the same can be said of research labs in other fields. In the distributed cognitive systems of Lab A, information processing technology plays an essential role in nearly all facets of data analysis, equally as well when the data-producing technology has no such technology connected with it, as in the EBSAD case, as when it is integrated with it, as in the mechanical tester case.

From the paper in a prestigious journal co-authored by the graduate student (A23) who instituted the mechanical tester within his lab, and the PIs of the two labs that have housed the mechanical tester at various times, one can hardly tell any of the specifics and no less the labor involved in the measurement and analysis procedure related to the mechanical tester. As with the figure showing the mechanical tester (*Figure 6* is but a slight modification from the figure shown in A23's published paper) the information technology has disappeared from the publicly shared account. In the paper's text the use of information technology is reduced to the mention of a "video imaging system" and a reference, in parentheses, to the *Matrox Inspector* software. No mention is made of the software controlling the motor and certainly no mention of the spreadsheet application and its uses. Probably, none of these omissions, if indeed one would want to call them that, comes as a big surprise to those familiar with the current standards and conventions of publishing in scientific journals. The use of software applications and utilities is assumed standard. The other side of the coin, however, is the treatment of measurement and data analysis procedures as purely instrumental affairs, as means towards an end, and therefore rendered as unproblematic as possible. Against this minimalist treatment stands the researchers' first-hand experience with the stories of measurement and data analysis. Thus, it is equally true for these researchers that in many ways measurement and data analysis are *the* problems.

Witnessing lab members engaged in measurement and data analyses we found that these procedures were at times spread out over days and weeks. In the case of the undergraduate intern's experiments involving the mechanical tester, she analyzed videotapes and data over weeks. In fact, the actual setting of the analysis consisted of her sitting in front of a computer screen at a PC located in a somewhat remote, windowless part of the lab, having a hand-held calculator on the table to her right and the analysis protocol sheet and a pen to here left. In our understanding of the laboratory as a distributed cognitive system evolving over time, this scene is a snapshot of a distributed cognitive system within the larger system. Measurement and computation are achieved by this system as a whole, with the human agent assuming various roles depending on the performed subtask. When coordinating her actions with the analysis protocol the student performed as the *researcher* in charge of the situation, when calling up files and software macros she performed as the *user* in a standard setting of human-computer interaction, when measuring wall thickness on screen she performed as the *seeing-eye agent* for the system.

Ed Hutchins (1995: 65) has characterized navigation aboard a Navy ship in similar terms pointing out how

> all the major computations in this system are based on procedures that involve measurement (which is analog-to-digital conversion), followed by digital manipulation, followed by digital-to-analog conversion in the plotting of results on a chart.

Much the same general terms were used by John von Neumann (1958: 68) to characterize a rather different system, "the digital and analog parts of the nervous system". In this context, von Neuman also spoke of the "mixed character" of the processes that go through the nervous system (1958: 69):

> Thus the nerve-pulse part of the system, which is digital, and the one involving chemical changes or mechanical dislocations due to muscular contractions, which is of the analog type, may, by altering with each other, give any particular process a mixed character.

We want to emphasize here that for the kind of distributed system that we have witnessed in the lab, analog and digital representations exist not only consecutively but also concurrently during an analysis procedure. In fact, their concurrent existence — or instant conversion — is, we think, a hallmark of these procedures.

Biologists and other scientists interested in the effects of certain conditions on cell morphology photograph cells through a microscope, using a digital camera, for later measurement and analysis. These micrographs are subsequently displayed on a computer screen and the researchers use a line tool provided by the image analysis software to make on-screen measurements of variables such as circumference, diameter or length. This procedure is widely known and used. The described analysis of the videotaped tests performed with the mechanical tester involves the same general procedure, only in this case the measurements are performed on frames of a videotape without any further imaging techniques (e.g., a microscope) intervening. In the case of the image analysis procedure related to the mechanical tester, the researchers make on-screen measurements of hook displacement and wall-thickness of the specimen, equally using a line tool provided by a software application. For hook displacement, the line that is fitted into the image *re*-presents the downward motion of the lower hook during testing; for wall thickness the lines drawn on the image of the specimen (six lines total to compute average wall thickness) are *virtual* cuts through the material at the respective places. In each of these cases, the cognitive system, comprising a computer supporting a software application and the user operating the line tool, takes advantage of the concurrent existence of a digitized image on one end and an analog on the other. The researcher, of course, is not only the user in front of the computer screen but also the agent who can take advantage of the system's dual strength, namely, to do well with the digital representation on the one end and with the analog on the other.

The concurrent representation of digital and analog representations by a system — or their instant conversion — characterizes modern information technology at least since the advent of graphical user interfaces. But the same concurrency has been long familiar from other artifacts, for instance, mathematical graphs drawn in a Cartesian coordinate system. Artifacts can also perform as analog computers. Hutchins (1995) emphasized this point for charts in navigation. Charts in navigation are different in this way from the graphical representations that we have encountered with the analysis procedures in the case of the mechanical tester. The stress-strain curve that is the "ultimate" outcome of these testing procedures is concurrently analog and digital - at least to the researchers who can read stress and strain as analog dimensions based on displacement and force.

Acknowledgements

We thank Wendy Newstetter for her contributions to the research on this project. We thank our research subjects for allowing us into their work environment and granting us numerous interviews. We gratefully acknowledge the support of the National Science Foundation ROLE Grant REC0106773.

Note

1 Although some of the material we quote from comes from published sources, given the regulations governing confidentiality for human subjects research, if the authors are among

subjects we are not able to provide citations to that material here. It seems that the possibility of conducting historical research in conjunction with human subjects research was not anticipated!

References

Abowd, G.D. and Mynatt, E.D. (2000), "Charting past, present, and future research in ubiquitous computing". *ACM Transactions on Computer-Human Interaction* 7: 29-58.

Arnstein, L.F. Sigurdsson, S., Borriello, G. (2001), *Labscape: Experiment capture in the biology laboratory*. Technical Report.

Bush, V. (1945), "As We May Think". *The Atlantic Monthly* 176.1: 101-108.

Arnstein, L. Hung, C.-Y., 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: 13-21.

Greeno, J.G. (1989), "Situations, mental models, and generative knowledge". In D. Klahr and K. Kotovsky (eds.), *Complex information processing*. Hillsdale, NJ: Lawrence Erlbaum.

Hutchins, E. (1995), *Cognition in the wild*. Cambridge, MA: MIT Press.

Nersessian, N.J. (in press), "Interpreting scientific and engineering practices: Integrating the cognitive, social, and cultural dimensions". In M. Gorman, R. Tweney, D. Gooding, and A. Kincannon (eds.), *Cognitive studies of science and technology*. Mahwah, NJ: Lawrence Erlbaum.

Nersessian, N.J., Kurz-Milcke, E., Newstetter, W.C. and Davies, J. (in press 2003), "Research laboratories as evolving distributed cognitive systems". In *Proceedings of the Twenty-fifth Annual Meeting of the Cognitive Science Society, Boston*.

Nersessian, N.J., Newstetter, W.C., Kurz-Milcke, E. and Davies, J. (2002), "A mixed-method approach to studying distributed cognition in evolving environments". *Proceeedings of the International Conference on Learning Sciences*.

Nersessian, N.J. (1992), "How do scientists think? Capturing the dynamics of conceptual change in science". In R. Giere (ed.), *Minnesota Studies in the Philosophy of Science*. Minneapolis: University of Minnesota Press.

Nersessian, N.J. (1995), "Opening the black box: Cognitive science and the history of science". *Osiris 10*. (*Constructing Knowledge in the History of Science*. A. Thackray, ed.): 194-211.

Neumann, J. von, (2000), *The computer and the brain*. New Haven, [STATE]: Yale University Press.

Resnick, L.B., Levine, J., and Teasley, S. (1991), *Perspectives on socially shared cognition*. Washington, DC: APA Press.

Taubes, G. (2002), "The virtual cell". *Technology Review* April, 2002: 62-71.

Weiser, M. (2003), *Ubiquitous Computing*. Internet Web page. http:www.ubiq.com/hypertext/weiser/UbiHome.html

Waldrop, M.M. (2001), *The dream machine: J.C.R. Licklider and the revolution that made computing personal*. New York: Penguin.

Gerassimos Kouzelis/Maria Pournari
Michael Stöppler/Vasilis Tselfes (eds.)

Knowledge in the New Technologies

PETER LANG
Frankfurt am Main · Berlin · Bern · Bruxelles · New York · Oxford · Wien

Bibliographic Information published by Die Deutsche Bibliothek

Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data is available in the internet at <http://dnb.ddb.de>.

We are grateful to the
STAVROS S. NIARCHOS FOUNDATION
for the financial support in the publication of this book.
A publication of the Society for the Study of Human Sciences.

Gedruckt auf alterungsbeständigem,
säurefreiem Papier.

ISBN 3-631-53782-4
US-ISBN 0-8204-7710-9

Printed in Germany 1 2 4 5 6 7

www.peterlang.de