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What has history to do with cognition? Interactive methods for studying research laboratories

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Abstract

We have been studying cognition and learning in research laboratories in the field of biomedical engineering (Nersessian, Kurz-Milcke, Newstetter, & Davies 2003, Newstetter, Kurz-Milcke, Nersessian, in press[a]). Through our combining of ethnography and cognitive-historical analysis in studying these settings we have been led to understand these labs as comprising evolving distributed cognitive systems and as furnishing agentive learning environments. For this paper we develop the theme of 'models-in-action,' a variant of what Knorr-Cetina (1999) has called 'knowledge-in-action.' Among the epistemically most salient objects in these labs are so called "model systems," which are designs that blend engineering with the study and use of biological systems for purposes of simulative model-based reasoning. We portray the prevalent design-orientation in this engineering specialty and how the prevailing activity of cell-culturing in these labs transitions into a design activity for the bio-medical engineers, leading them

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to work with 'wet' devices. We discuss how devices, 'wet' and 'dry', situate model-based understandings and how they participate in model systems in these labs. Models tend to come in clusters or configurations, and the model systems in these labs are epistemically salient junctures of interlocking models. Model systems in these labs evolve thereby consolidating what we want to call a 'fabric of interlocking models,' which functions as point of stability and departure in these labs. We convey a taste of such a 'fabric' for a tissue-engineering lab. We conjecture that through this 'fabric' extended developments in technology and methodology have a 'situated' presence in the workings of these labs.

1. Introduction

Cognitive scientists have, at times, made a point out of their leaving the psychological laboratory to study cognition in settings, in which people live, learn and work. Research laboratories are such a setting, and we (see Nersessian, Kurz-Milcke, Newstetter, & Davies 2003, Newstetter , Kurz-Milcke, Nersessian, in press[a]) have been studying cognition and learning in research laboratories in the field of biomedical engineering (BME). Research laboratories are sites of scientific work, and university laboratories, in particular, are also charged with the task of training students and housing their degree-relevant research. The laboratories that we have been studying are part of a university system and are located on a university campus. Some of the researchers in these labs are at the post-doctoral level, but most are graduate students working towards a Ph.D., many of these have undergraduates working with them being on various types of rotations and internships, some undergraduates stay extended periods (a year or two or even longer) and some develop quite independent research projects. The Principal Investigators of these labs, for short, the PIs are typically not involved in benchtop activities. They are

charged with the task of grafting and representing the research agenda of their lab, to communicate results and problems, to secure funding, to furnish and maintain contacts with other labs and institutions, to attract students to the lab, and last but not least to oversee the lab's research activities and advise lab members. Through meetings with the individual lab members and lab meetings, PIs are supervising most all research projects in the lab, at least to some degree. In short, these laboratories comprise various social arrangements, institutions, and in various spaces, implicating particular lab members in differential ways.[1]

'The lab,' and for good reasons, is often equated, also by the researchers themselves, with those spaces that house the lab-specific equipment and instrumentation and the various workbenches. In the case of BME, some of these benches are sterile and 'wet,' others are joyfully cluttered with metal and plastic parts and the respective work tools, and some with cables and eviscerated electronics. In some situations, however, the notion of 'the lab' is meant not primarily as a reference to a set of salient spaces but rather as a reference to a research agenda and the group associated with it. Thus, 'the lab' has multiple meanings associated with it, as have many objects *in* 'the lab,' especially those that are salient *with* 'the lab's' research activity. This multiplicity in meaning carried, quite generally, by the salient objects in the lab, where saliency derives from their epistemic function, contributes in an important way to the argument that we are developing in this paper. In particular and through our studies of BME laboratories we

[1] As an engineering specialty BME has a relatively high proportion of women working in this field, currently about 30%. What has been referred to as 'critical mass' in the literature on gender and professional training and education is consequently easily found in BME labs (Malone, Nersessian, & Newstetter in preparation). In one of the labs that we have been studying at one point the gender distribution (which is subject to some fluctuation as lab members join and leave) was such that 11 out of 15 lab members were women.

have learned about the saliency of "*model systems"* in this field. Model systems are engineered systems but at the same time they are sites for systematic experimentation. What is more, model systems incorporate models, just how, has become increasingly a topic for us in studying these labs.

With our combining of ethnography and cognitive-historical analysis (Nersessian, Newstetter, Kurz-Milcke, & Davies, 2002) in studying BME laboratories we have been led to flesh out a genetic orientation in a three-fold manner.[2] First, we have come to understand these labs as comprising *evolving* distributed cognitive systems, emphasizing a *diachronic* dimension for the case of distributed cognition. Second we have come to understand the epistemic salience of a particular class of objects, the model systems, to which the labs, each to their particular instances, uphold a special commitment. This commitment plays out in the form of a prolonged and intense investment of resources, and in the participation of at least one of these systems in nearly all of the research projects in a lab, which, in turn, is a circumstance that encourages their evolution. Third, we have been interested in these labs as learning environments and in understanding the patterns and trajectories of participation with these settings as they have been described with *communities of practice* (Lave & Wenger, 1991, p. 101):

[2] The sociologist and ethnographer of laboratory science, Karin Knorr Cetina (1983, 117) has long advocated a "genetic orientation" with "the ethnographic study of knowledge production at the actual site of scientific action," for our purposes, of 'the lab.' In fact, this orientation has gone along with an understanding of scientific practice as *locally situated* (Knorr Cetina 1983, p. 123). Thus, the genetic orientation is here occasioned by the study of the "circumstances of production," or as Knorr Cetina put it subsequently, of the respective *epistemic culture* (Knorr Cetina, 1999). Circumstances of production are evolving, and especially significantly with research laboratories in fields that are 'hot' at the time. We think that biomedical engineering has been, for a number of years now, and currently continues to be, just such a field.

> Becoming a full participant certainly includes engaging with technologies of everyday practice, as well as participating in the social relations, production processes, and other activities of communities of practice. […] Participation involving technology is especially significant because the artifacts used within a cultural practice carry a substantial portion of that practice's heritage […] Thus, understanding the technology of practice [sic!] is more than learning to use tools; it is a way to connect with the history of the practice and to participate more directly in its cultural life.

For our purposes, it is important to draw attention to the fact that the laboratories that we have been studying, by their (self-)assigned task to innovate in the area of design with biological materials and systems, are rather forward-looking communities. We think that in this dimension they are different, certainly in degree, from the communities of practice that are referenced in Lave and Wenger's (1991) *Situated Learning*, of which the above is a quote.[3] This difference has mattered, in our estimate, to how "history" has entered their account in this case, namely as "heritage." Somewhat ironically, our stance is that for our purposes here, 'history' as heritage is not sufficiently 'situated '. The opportunity with the cases at hand is to think 'history' in a exceedingly situated fashion, namely, in relation to laboratory practices and their cognitive dimensions. We are the first to admit that this is not the only possible, even generally appropriate kind of 'history.' However, we think that with the study of these labs, a highly 'situated' account it is one of the desirable historical perspectives, others are, for instance, histories of particular objects,

[3] See Lave & Wenger (1991), chapter 3: "Midwives, Tailors, Quartermasters, Butchers, Nondrinking Alcoholics"

disciplinary histories, or cultural and social histories pertaining to science and engineering.[4]

The theme for this paper is *models-in-action*, a variant of Knorr Cetina's (1999, p. 3) "knowledge-in-action," as it applies to BME research practices.[5] Specifically, for this paper we have chosen to concentrate on the model systems in these labs and how they implicate models and simulative model-based reasoning. The emphasis here is on the cognitive implications of the benchtop model and its epistemic functioning; we are not addressing issues of 'internal' cognitive representation with this paper. The larger argument that we see implicated here is that cognitive theorizing has no natural boundary to work with, and no harsh distinction between the internal and the external (see also Nersessian, in press). When we argue for 'the BME benchtop' in this paper, we not only mean a set of workspaces in the laboratory but a coming together of embodied action, tools, materials, representations, social arrangements, and their situated historical connections that make the activity in that place at that moment possible, and meaningful.

Simulative model-based reasoning thus occurs at, on, and in conjunction with 'the benchtop.' Reasoning, as in 'model-based reasoning' (see Nersessian, 2002b), is not primarily identified with argument and logic in these situations but with the formation,

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[4] We want to note here especially historically oriented work on modern laboratory research (e.g., Shapin & Shaffer 1985, Holmes 1991, Soderqvist 1997).

[5] In her recent book Karin Knorr Cetina introduced the notion of "*epistemic cultures* " as "cultures that create and warrant knowledge" (Knorr Cetina, 1999, p. 1). Whereas the notions of discipline and specialty preferably refer to the "differentiation of knowledge," and thus to the (institutional) organization of knowledge, *epistemic culture* shifts the focus of attention to "knowledge-in- action" (Knorr Cetina, 1999, p. 3). As an approach to the study of expert practice it refers to a characterization of "knowledge making machineries" and their respective expert competencies (Knorr Cetina 1999, p. 3). Furthermore, the notion of epistemic culture is equally implicative - as have been the earlier notions of *discipline* and *specialty* . The notion of epistemic culture addresses how different such cultures play off of each other. For her project of studying the differences in knowledge-making machineries in the sciences, Knorr Cetina sought out the contrasting cases of high energy physics and molecular biology. The case that we have been studying with BME is especially well-suited for this perspective in that these laboratories seek an explicit melding of

maintenance and selective expansion of simulative capabilities. Simulation, of course, is a thoroughly epistemic activity and endeavor, its intent being that of fostering insight and supporting inference through the creation of situations and processes resembling those of interest in a selective and meaningful way. Etymologically, deceit originally seems to have taken the upper hand over insight in the meanings ascribed to 'simulation' and the related verb 'to simulate,' indicating the apparent as a mere counterfeit and only then as the aesthetically, structurally, or procedurally analogous. Similar to the ever-critical notion of the 'symbol' in the study of cognition, 'simulation' blends perception with artifact in order to render something apparent. This blending into one another of cognitive capabilities and artifacts gives the traditional field of meaning for 'simulation' (and its related terms), which spans actions of deception, observant and lyric descriptions of nature, the suggestively antagonistic nature of board games, as well as technologies serving the aim of computational modeling (see *The Oxford English Dictionary*).

In the cognitive literature, the notion of a *mental model* is employed to indicate a temporary structure that is created in working memory during comprehension and reasoning processes.[6] Simulative reasoning takes advantage of "the knowledge embedded in the constraints of a mental model to produce new states" (Nersessian 2002b, p. 149). In the form of *thought experiments* this type of reasoning is most often associated with exceptional situations and scientific thought. However, even in the context of scientific writings thought-experimental narratives often rely on familiar experiential dimensions of human activity and cognitive processing (and interestingly often in a counterfactual way

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practices from different epistemic cultures. We propose that the "model systems" discussed in this paper are among the most important dimensions of this melding as the biomedical engineers pursue it.

[6] Nersessian (2002b) spells out the two main usages of the term 'mental model,' namely as (1) structure in long-term memory, and (2) as temporary structure created in working memory.

rendering a certain outcome or a course of action highly unlikely given familiar experiential constraints; see Gooding 1992). More generally, simulative reasoning is increasingly theorized to be constitutive of human cognition in a encompassing fashion, where the human conceptual system is understood to be predicated on forms of re-enactment, and concepts evoked in reasoning are thought of as 'simulators' constructed for the purpose of supporting situated action (see Barsalou 2003, Prinz 2002). In this paper we approach simulative model-based reasoning from the benchtop model and not predominantly from the mental model *per se*.

Model systems, we seek to convey with this paper, more than any thing function as situations that allow for simulation and in that they are culturally and cognitively informed, technological, and historical in character. Model systems in these labs are not just 'any old situation,' they are most carefully and persistently grafted but just as 'any old situation' they are bit beyond human control. This "bit" we attempt to show is most significant with the research in these labs, in part suggesting an independent contribution of the biological, mostly cell-based systems that take part in the engineered designs developed by these labs. Most of all, as 'situations' the researchers can operate *within* these model systems in ways that are similar to someone operating within a framework, only this time the intent is simulation and the activity is highly embodied and somewhat heavy on the technology.[7]

We begin, in section 2. *Combining Ethnography with Cognitive-Historical Analysis*, by outlining our combining of methods and by discussing their interactive

[7] Another way to express this embodied, technology-based and somewhat astounding state of affairs in which a human being is placed within a situation that is otherwise known as a model system is to think of this state in analogy to a cyborg, i.e., a personified technology-based enhancement of human capabilities (see Clark 2003).

value, as it has been important to our 'laboratory studies' so far. With section 3. *'Models-in-Action:' Design-Oriented Laboratory Practices in BME* we address the theme of this paper, which relates the design-orientation in BME to the epistemic saliency of model systems in these settings. We introduce the notion of 'interlocking models' in relation to these model systems, and we describe how interlocking models in their historical development form 'fabrics of interlocking models.' And finally, with section 4. *Discussion: What--in the lab-- has history to do with cognition?* we address how a 'situated' historical understanding of technologies in the lab can function as a permission and resource for re-engineering and for aspiring to novel designs.

2. Combining Ethnography with Cognitive-Historical Analysis

To date, ethnography has been the primary method for investigating situated cognitive practices in distributed systems. Ethnographic analysis seeks to uncover the situated activities, tools, and interpretive frameworks utilized in an environment, that support the work and the on-going meaning-making apparatus of a community. Ethnographic studies of situated socio-cultural practices of science and engineering are abundant in science and technology studies (STS; see, e.g., Bucciarelli 1994, Latour & Woolgar 1986, Lynch 1985). However, studies that focus on situated *cognitive* practices are few in number in either STS or in cognitive science. Further, existing observational (Dunbar 1995) and ethnographic studies (See, e.g., Goodwin 1995, Hall, Stevens, & Torralba 2002, Ochs & Jacoby 1997) of scientific cognition lack attention to the kind of genetic, i.e., 'situated-historical,' aspects that we find important with our case studies. As a method, ethnography does not, generally, seek to capture the critical *historical* dimension of the

research lab: the evolution of technologies, agents, and problem situations over time that are central in interpreting the current practices.

In the same vein, conceptions of distributed cognition in the current literature fail to account for systems that undergo significant changes both on long and short time scales. In Hutchins's studies of distributed cognition in work environments, for instance, the cockpit of an airplane or on board a ship, the problem solving situations change in time. The problems faced, for example, by the pilot, change as she is in the process of landing the plane or bringing a ship into the harbor. However, the nature of the technology and the knowledge the pilot and crew bring to bear in those processes are by-and-large stable. Even though the technological artifacts have a history within the field of navigation, such as Hutchins documents for the instruments aboard a ship, these do not change in the day-to-day problem solving processes on board. Thus, these kinds of cognitive systems are dynamic but largely *synchronic*. In contrast, the cognitive systems of the BME research laboratory are dynamic and *diachronic*. The things in the lab and especially those that are epistemically salient are evolving, being potentially always under revision. To a certain extent they perform as "ratchets" for this epistemic culture (see Tomasello 1999), in that they are passed down to new generations of researchers who must familiarize themselves, hands-on, with the artifact in its current instantiation, come to know relevant aspects of its history in the research program, and figure ways to use it or possibly modify it to fit new research problem demands. In many instances researchers are able to reconstruct their histories, placing these within an evolving problem situation. For example, a senior Ph.D. researcher and "resident expert" on a

device referred to as "bioreactor," reconstructed on the spot for us some of its history within the lab:

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

He continued by pulling down previous versions of bioreactors (made by earlier researchers as well) and explaining the modifications and problems for which design changes were made. It struck us in the account of the evolution of this device that the necessity of re-design *historicizes everything*. So in a larger sense, history as articulated here is not primarily a matter of narrative but of engineering action in relation to the biological world.

Cognitive-historical analysis enables following trajectories of the human and technological components of a cognitive system on multiple levels, including the physical shaping and re-shaping of artifacts in response to problems, their changing contributions to the models that are developed in the lab and the wider community, and the nature of

the concepts that are at play in the research activity at any particular time.[8] As with other cognitive-historical analyses (Gooding 1990, Gorman & Carlson 1990, Kurz 1997, Kurz & Tweney 1998, Nersessian 1992, 1995, 2002a, Tweney 1985, 1992, 2001), we use the customary range of historical records to recover how the representational, methodological, and reasoning practices have been developed and used by the BME researchers. The practices can be examined over time spans of varying length, ranging from shorter spans defined by the activity itself to spans of decades or more. Cognitive-historical analysis interprets and explains the generativity of these practices in light of salient cognitive science investigations and results (Nersessian 1995). Saliency is determined by the nature of the practices under scrutiny. In this context, the objective of cognitive-historical analysis is not to construct a historical narrative. Rather, the objective is to enrich understanding of cognition through examining how knowledge-producing practices originate, develop, and are used in science and engineering domains.

Given our understanding of culture as an inherently historical notion, we believe our interactive methodological approach to studying cognition and learning in BME research laboratories is applicable to laboratory studies more widely. However, since we have only studied these kinds of labs, we discuss our approach in reference to them. Several perspectives are possible with respect to the here advanced combining of methodologies, the crudest of these being that each approach can provide something beyond and above the other. Through observations, interviews, and the compilation of inventories, ethnography has allowed us to gain an understanding of the activities, of the material and social culture, and of the self-understanding of the labs and their members.

[8] For a comparison of cognitive-historical analysis to other methodologies – laboratory experiments, observational studies, computational modeling – employed in research on scientific discovery, see (Klahr &

Based on the customary range of materials for historical analysis, and to some extent on interviews, our cognitive-historical analyses has allowed us to construct and analyze the individual and combined trajectories of the people and objects in these labs, and to some extent of the labs and the wider research fields (although we have not been concentrating on the latter).

A different and in many ways more adequate perspective on our combining of these methodologies is that in their interaction they have served to constrain each other and the ways in which we have been constructing the labs as research objects. Observations over many months, collected materials, and interviews enforced the point that these settings are in important and rather rapid ways evolving, which includes the shifting to novel research problems and to novel means to explore and solve them within the lab. In addition, new lab members are almost constantly brought in, then staying for various length of time, and the more permanent lab members change their patterns of participation depending on where they stand career-wise or degree-progress-wise. Material artifacts, especially the devices, go through cycles of redesign, and lab spaces become differently allocated depending on the latest research projects. Based on our bringing into interaction these methods we have come to characterize these laboratories as *evolving distributed cognitive systems*. With this designation we recognize the distributed cognitive nature of the laboratory and its various project-related subsystems. Relatively circumscribed subsystems based on set-ups and projects can be singled out and the generation and propagation of representations through these can be documented and analyzed (e.g., Nersessian, Kurz-Milcke, & Davies, under review).[9] However,

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Simon 1999).

[9] To browse this manuscript the reader can go to http://www.cc.gatech.edu/aimosaic/faculty/nersessian/

acknowledging the evolving nature of these distributed systems does more than adding a qualifier, it has led us to conceive these systems in relation to a more holistic understanding of the lab and its research agenda (which is also evolving). In other words, the research in these innovation-affording settings does not merely live off of what is presently possible given its material and representational resources, but lives to a good extent on the promise that additional and novel resources can be brought on board to address old and new agenda-related problems. At this point we feel compelled to at least speculate that this type of optimism about future resources and options is inseparable from engineering as a cultural endeavor in technologically advanced societies.[10] Thus, we have found it pertinent to consider these laboratories also as problem spaces with permeable boundaries, and to analyze them on the background of what they are trying to achieve in terms of their agendas, namely, finding as of yet unknown design projects and solutions.

Construed in this way, the notion of problem space takes on an expanded meaning from that customarily employed in the traditional cognitive science characterization of problem solving as search through an *internal* representation in an individual mind. In line with the traditional characterization, the notion serves the purpose of signifying a space in which cognitive processes can be theorized. But when these processes are viewed as lying with a distributed cognitive system, the notion or 'problem space' needs to encompass multiple and varied media ranging from the human conceptual system to instruments and devices, and multiple agents. And, thus, the metaphor of problem solving as search is inadequate to capture the constructive processes implicated in the

[10] An essay speculating in the same direction can be found in Ortega Y Gasset's (2002) "Man the Technician," where it is argued that the modern, culturally methodical pursuit of technological advances

varied forms of problem solving that we find with these research labs[11]. These processes, involving material, discursive, and modeling processes and involving multiple agents and varied artifacts, are distributed across evolving systems.

A related, but somewhat different perspective on our combining of methodologies has emerged for us from having been in close proximity to the action in the lab and the lab members during their daily activities, conversations and dealings with each other. In this perspective, which we have tentatively labeled *cognitive-historically situated ethnography*, human agents are implicated as persons. This designation bears obvious resemblance to "cognitive ethnography," the designation that Hutchins (1995, p. 371) introduced with his call for descriptions of "cognitive task worlds" as they exist in "culturally constituted settings." What has become salient for us with these laboratories is that most of the lab members persevere in the face of great failure due to many factors in the lab such as suddenly dying cell-cultures, recurring malfunctions of instruments, severe problems with materials used to engineer devices, incomprehensible outputs of instruments and many other issues. We are mentioning these motivational issues here to point out that in order for us to understand what Hutchins (1995, p. 372) has referred to as "culturally constituted activity" involving the "whole human being," in the case of these labs we need to take account of systems that require considerable commitment and tolerance for uncertain outcomes on the part of the human beings partaking in these.

Here again, we think that a 'situated' understanding of the notion of commitment is called for; commitment is not merely a pre-condition that students somehow have to

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has led to the conviction that new technological discoveries are a certainty.

[11] See Gooding (1990) for a corresponding graphical adaptation of the problem space notion in his experimental maps of Michael Faraday's experimentation. See Kurz-Milcke (2004) for a related critique and proposal to substitute the prevalent spatial representation of problem solving.

bring with them to begin with (well, some of that may be required) but rather a condition that needs to be and is sustained by the laboratory setting. This point is not the particular focus of this paper but we want to bring out here at least that these settings encourage participants to seek out other agents, human and non-human, to achieve learning and increased participation, and to provide learning opportunities for other participants (Newstetter, Kurz-Milcke,Nersessian, in press[b]). Everyone is a learner here—the undergraduates, the Ph.D. candidates, the post docs and the principal investigator. This feature of constant uncertainty created by an insufficient knowledge base turns out to be a good thing for learners. Another feature that seems to serve learning is the distributed nature of cognition. The complexity and interdisciplinarity of the laboratory problems means that knowledge or understanding does not reside inside single individuals but is rather distributed or stretched across people, devices, texts and other lab instruments and artifacts. For these reasons, we have come to characterize the learning in these settings as agentive. The notion of *agent* emphasizes how these learning cultures afford and sustain the formation of relationships between agents. Agentive in this sense implies the person/learner, who is characterized by her relationships to other agents (in distinction to the individual who would be characterized essentially by her separation from other participants.) Its relation to the notion of *agency* emphasizes that these learning cultures depend on human agents who are authorized to enlist other entities, human and nonhuman, as agents in their work and understanding.

3. 'Models-in-Action:' Design-Oriented Laboratory Practices in BME

3.1. The all pervasive design-orientation in BME

Biomedical engineering (BME) is an *interdiscipline* in that melding of knowledge and practices from more than one discipline occurs continually, and significantly new ways of thinking and working are emerging. Innovation in technology and lab practices is programmatic, and learning, development, and change in researchers are constant features of the lab environment. In a way, these laboratories qualify not merely as sites of knowledge construction but also as sites for "the construction of the machineries of knowledge construction" (Knorr Cetina, 1999, p. 3). These laboratories embark very decidedly on a program of reconfiguration, playing off of the knowledge and practices of concurrently existing, well-established *epistemic cultures* (Knorr Cetina 1999) in engineering and the biological sciences, and off of themselves in a process of evolution and design.

BME has as its programmatic outcome engineered artifacts built at least in part from biological components, for example, an actual blood vessel substitute (as in tissue engineering Lab A) or a 'trained' neuron culture for operating a robot (as in neuroengineering Lab D). In fact, the desire of most researchers in these BME laboratories is to interact with these visionary objects and to work their design. Notably, these epistemically mixed objects of desire, being simultaneously engineered and biological, reflect back on the engineers' understanding of biological systems and processes recasting them from a design perspective as well. The following quote by the PI of Lab A may serve as an illustration for this expansive design orientation [emphasis added to original transcript]:

PI: Well, it was clear to me from reading the literature that, and what was really motivating me by 1970-1971, was the fact that these characteristics of blood flow actually were influencing the biology of the wall of a blood vessel. And even more than that, *the way a blood vessel is designed*. [It follows a longer pause.]
Interviewer: So, this was influencing the characteristics of the biology
PI: Yes, right, and influencing biological processes that were leading to disease. *The way a blood vessel is designed is*, it has an inner lining, called the endothelium. It's a monolayer, we call it a monolayer of cells because it's one cell thick. But it's the cell layer that is in direct contact with flowing blood. So, it made sense to me that if there was this influence of flow on the underlying biology of the vessel wall, that somehow that cell type had to be involved, the endothelium.

Thus, for these labs, the notion of design extends beyond the design of engineered artifacts and also beyond the design of the lab as a locale in which student researchers with various disciplinary backgrounds are brought behind a common research agenda. Furthermore, these BME labs intersect in various ways with an educational setting that has as its goal to train "biomedical engineers" from the outset in contrast to the traditional model of collaboration among engineers, biologists, and medical doctors. The desire is to shape a new kind of expertise, which by design would shorten the stretch between laboratory research and medical application.[12]

[12] The BME culture as we have been witnessing it in these laboratories and in the respective institute is approaching certain features of what has been described as 'Mode 2' knowledge production, which is

3.2. From cell-culturing to cell-based devices

Cell-culturing is a prevailing activity in these BME labs. For most newcomers to these labs, culturing of cells is one of the first sets of practices in which they actively participate and a significant inroad to becoming part of the lab. Most of these students have an engineering background and are not particularly familiar with work on the sterile workbench. Generally speaking, the culturing of cells per se needs to emulate the natural occurring conditions of living tissue in an organism to the extent that cells are required to survive and perform in particular ways. This emulation assigns particular tasks to the laboratory environment as it applies to cells, for instance, the careful supply and monitoring of CO_2 levels in incubators. This emulation also leads to particular understandings of cells as lab objects, which in turn imply particular roles for the researchers. Cells require a certain level of 'babysitting' (as lab members have been overheard calling it) in terms of care and commitment. The required skills are learned in apprenticing relationships, mostly one on one.

For the process of learning to cell-culture in the context of tissue-engineering, we have identified three stages (Newstetter, Kurz-Milcke, & Nersessian, in press[a]). Initially, learning to culture cells entails focussing on those actions that are done to the culture. Cells can be moved, fed, looked at under microscopes and counted, split or frozen. As time passes, and, this can happen very quickly, things happen to the cultures

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characterized among other features by "transdisciplinarity," "flat hierarchies" and consideration of "the context of implication"(See Nowotny 2003). The innovation-affording nature of the research leads generally to a learning culture that despite its degree- and position-based hierarchies is in many aspects of daily practice better characterized by "flat hierarchies." What is more, the educational program that is currently in the process of being instituted in this particular BME institute and which receives wide support from faculty and students in the institute is specifically built around small working groups that tackle '*real'*

that begin to suggest that cells are agents, as are children and pets. Indeed, a graduate student was overheard telling a newcomer: "Think of them as children or pets." Often, this quality of cells requiring care and supervision but also acting and reacting seems to work to the detriment of the learner. Cultures die; they "go bad." They ruin experiments and require long weekends of "babysitting." They are now seen as objects with specialized needs, which require actions and behaviors on the part of the learner. This new understanding of the culture now entails both cells as objects that are acted on, but also reacting (often negatively) to environmental conditions. Interestingly, the PI of a tissue engineering laboratory related to us that it was not uncommon for learners to "get stuck" in this stage. But to move forward in their research, students have to move beyond this understanding of the cell culture to a different, more involved relationship with, and understanding of cells-in-culture. We see this understanding with the more advanced lab members and with other senior researchers in this research area. At this stage, cell cultures are understood not only as systems that react but also as systems that have capabilities that can potentially be enlisted for design purposes.

At this advanced stage, learners come to see the cells as potential 'partners' in the research process. This new understanding of the cells as rich systems implies the potential for a working relationship. The cells can now do things with and for the researchers. Possibly against common belief, it is at this advanced stage of the relationship at which anthropmorphizations involving mentalistic language occur in the most self-assured fashion. Here are some examples of such accounts of cell activity, the first by a member of Lab A (emphasis added to the original transcript):

(as opposed to textbook) *problems* in a fashion that cuts across disciplines but also seeks to take account of the varying *stakeholders* in each case (LaPlaca, Newstetter, & Yoganathan 2001).

> A11: Um well, the cells once they are in the construct [the artificial blood vessel constructs] will *reorganize* it and *secrete* new matrix and kind of *remodel* the matrix into what they *think* is most appropriate.

Similarly, we offer a quote from a lab meeting of Lab A, where in a discussion one of the lab members said (emphasis added to the original transcript):

> A7: I am not sure that the endothelial cells *like* that hybrid [she is referring to a particular kind of artificial blood vessel 'construct']…It is also important that the endothelial cells *see* their neighbors, smooth muscle cells.

This and the previous quote were from researchers at the level of advanced graduate students. Our final example is by the PI of neuro-engineering Lab D, who responded to a question from the audience at a plenary address explaining (emphasis added to the original transcript): "Cells *make a lot of decisions* with whom they *want to connect* with."

For biomedical engineers cellular systems have design quality, and can feed into design options. Consequently, these BME labs are culturing cells not only in Petri dishes or flasks, (which is important in terms of a sufficient supply of cells at particular stages of development) but in addition they work with 'wet' devices, that is, designs involving cell-cultures. Cell cultures have become part of engineered structures, such as tiny silicon tubings prepared in ways that allow cells to attach and grow on them (the artificial blood vessel "*constructs*" in Lab A; see Figure 1); or arrangements of electrodes, so called multi-electrode arrays (MEAs), which are prepared to function as culture dishes allowing

the recording and stimulation of developing neural networks (the "MEA dishes" in Lab D). Associated with this appreciation for the richness of cellular systems, is the understanding that these systems can only be modeled, 'wet' and 'dry,' in partial and selective ways.

We have here been focussing on one particular and crucial dimension of the activity of cell-culturing, namely, how the perceived nature of the cell-cultures changes in relation to mastery of this task. Cell-culturing, of course, is very much a hands-on activity involving the trained and skilled handling of equipment such as pipettes, and lids on dishes and flasks. For example, to be able to work an "assembly line," as one researcher put it observing a highly skilled lab member working at the sterile workbench with 15 or so culturing flasks in one session, one has to be able to hold and unscrew the flasks' tops with one hand while working the pipette with the other, all the while being careful not to reach with one's latex-gloved fingers over the tops of open containers (to minimize the chance of accidental contamination of the cell cultures). One also has to have all utensils, including the appropriate culturing medium in sufficient amounts ready at hand. This type of swift and precise handling requires on-task training (and we have heard that lab member have taken empty flasks home for practice), including the respective skills for planning out the activity (having to leave the sterile workbench during a culturing session is another potential invitation for accidental contamination). These activities are to a good degree apprenticed, where newcomers sit next to, or lean over a more experienced lab member as he or she is working at the sterile workbench, watching, asking questions, and receiving advice, then trying on their own, often supervised. Cell-culturing is a thoroughly embodied activity, and the understanding of cell-cultures in

these labs is to a good deal about meaningful activities performed on and, eventually, *with* these.

3.3. From devices to model systems

Certain objects in these labs more than others have the power to bind research projects together and to the respective lab's evolving research agenda. These objects can be thought of as *signature objects* of a lab, often being to a considerable degree assembled in the lab and playing a significant role in the "initiation" process for new lab members.[13] Based on a classification of the "things in the lab" that the members of Lab A carried out in a group session facilitated by us, we have found that most of these signature objects are what the lab members in Lab A refer to as "*devices"* (engineered in vitro models and sites of simulation). Many other objects are significant in the lab's research, some were classified as instruments (enabling measurement), others as equipment (assisting with manual or mental labor). Devices are the most salient objects in Lab A in that they are sites for simulating models of in vivo processes. Among the devices in Lab A are the *flow loop* (see Figure 2), which exposes cells-in-culture to flow and to the associated shear stresses, the *bioreactor* (see Figure 3), which exposes blood vessel constructs to pulsatile distension, and the artificial blood vessel constructs (see Figure 1), themselves. The latter being a 'wet' device. One or most often a combination of 'wet' and 'dry' devices forms a significant part in practically every research project that is carried out in this lab. We are currently in the process of determining whether and how this classification is prevalent and applicable in the understanding of other BME labs. But we can say this much,

[13] A senior lab member in Lab A related to us that the initial setting up of *flow loops* by newcomers was "one of the initiation rites" in the lab. [2003-04-29-I-A-A23-history.doc]

signature objects in these tissue-engineering laboratories, whether devices or instruments, are physical artifacts interfacing with living cell cultures.

It is in relation to the researcher(s)'s intent of performing a simulation with the device in order to create new situations that parallel potential real-world situations, and the activity of the device in so doing, that qualifies a device as a cognitive artifact within the system. Following Hutchins (1995), cognitive processes reside in a *cognitive system* comprising one or more researchers and the *cognitive artifacts* (see also, Norman 1991) involved in a problem solving arrangement. Cognitive artifacts are material media possessing the cognitive properties of generating, manipulating, or propagating representations.[14] For example, one of the devices, the flow loop, *represent*s 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.

In general, signature objects in these BME labs are cognitive artifacts. What distinguishes these artifacts from other cognitive artifacts, for instance, from a spreadsheet-based computer application like Excel used for statistical analyses of

[14] For related notions in the STS literature, see also (Rheinberger 1997) on "epistemic things" and (Tweney 2002) on "epistemic artifacts."

experimental data in the lab, is that these engineered artifacts are also sites for biological experimentation, as it is understood by these labs. Cognitive artifacts that qualify as signature objects are not merely model instantiating artifacts but *model systems,* an expression used by the BME researchers, at least the senior ones. As model systems, they are sites of systematic experimentation. In BME, these model systems *parallel* in vivo phenomena, biological processes and systems. This parallelism between in vivo phenomena and model systems (*qua* signature objects *qua* cognitive artifacts) is a deliberate – and not unproblematic—achievement that is continuously evolving if only in minor ways. Thus, *parallelism* in this case should be read as a historical process (*situated*), not the least because these model systems are not fast-lived set-ups but sites of serious investment over considerable time spans, typically by a number or generations of lab members.

Devices participating in *model systems* are double-referential by pointing at once to the properties of biological systems and to the properties of an engineered system. It is not principally a new point that objects implicated in scientific inquiry are double-, if not multi-referential. Gooding (1990, p. 13) has made this point with respect to "manipulated objects" in experimental inquiry, Knorr Cetina (1999, p. 112) with respect to "imaginative terminological repertoires" co-existing with technical language in science,[15] and Morgan and Morrison (1999) with respect to scientific models as "mediators" between theory and the world. Obviously, depending on their research interests, these

[15] The quoted anthropomorphizations involving mentalistic language describing the behavior of cells in culture by advanced researchers (section *Cognitive Partnering*, e.g., "Cells make a lot of decisions with whom they want to connect with.") are, we think, instances of such an imaginative terminological repertoire. Cells are often and in many ways anthropomorphized in this research area, interestingly, this terminological repertoire branches out into more strictly theoretical accounts through information

authors have focused on differing objects when arguing this point.[16] We have been interested, led by out investigations in the field, to focus on signature objects in the BME laboratories, especially devices. By pointing out this ambiguity we are referring to a prevalent property of scientific and technological objects. In each instance the analysis derives its relevance from being specific about how particular objects are *multi-referential*.[17]

Devices perform as part of model systems by instantiating current understanding of properties and behaviors of biological systems. In the words of an advanced graduate student working in a neuro-engineering laboratory, and here responding to a direct inquiry about his understanding of the notion of a model system (emphasis added to the original quote) :

> D21: But yeah I think I wouldn't describe my cell cultures as a model system and I wouldn't' describe.. *well the device could be a system in and of itself*, *when everything comes together I would call it a model system* […]I think you would be very safe to use that [notion] as the integrated nature, the *biological* aspect

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processing models (Kurz-Milcke, talk given at the Cognitive Colloquium, Georgia Institute of Technology, October 2002).

[16] Still another instance of this argument can be found in Dogan (2003) where the double referentiality of "conceptual diagrams" in architectural practice has been analyzed.

[17] Merz (1999) has used the notion "multiplex" to describe a related but slightly different characteristic of an object used in physics research, in this case computer programs used for simulation, so called "event generators." She emphasized for these the different object conceptions with different actors, which are related to the multiple purposes and goals in the research process. For the cases that we have been studying with these engineered devices it has been important to emphasize how they are 'multiple' for the same actor, granted that not all of their model-based dimensions are simultaneously heeded to an equal extent (see text above). Merz' (1999) case has a slightly greater emphasize on the objects' social embedding, whereas ours a slightly stronger emphasis on the objects' material embedding. The two leanings should be variably complimentary depending on the studied objects and cases.

coming together with an *engineering* aspect, so it's a *multifaceted* modeling system I think that's very good terminology to describe that.

In this fashion, model systems comprise a set of models. In the area of tissue engineering, for instance, some of these models refer to physiological aspects, which can include model understandings of the structures or of the functions of the vasculature and of the interrelations between structure and function at that level, some models refer to the cellular or to the tissue level, which can again refer to the respective morphology or to aspects of the biochemistry at that level and to their interrelations, still others point to mathematical model understandings and specifications that can serve to further constrain design options, experimentation or model understandings of the studied biology. This coming together of models in "multifaceted" complexes we refer to as *interlocking models*. In BME, engineered model systems incorporating biological and especially cell-based materials are focal interlockings of models of varied kind deriving from varied research practices and fields.

Devices in these research settings are systems in and of themselves, possessing engineering constraints that often require simplification and idealization in instantiating the biological system they are modeling. For example, the *flow loop* in Lab A is constructed so that the behavior of the fluid is such as to create the kinds of mechanical shear stresses experienced in the vascular system. As one researcher put it, this device 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." So,

as with all models, devices are idealizations (some BME researchers prefer the phrase "controlled environments" instead). Simultaneously, they are engineered, material objects that have to be built and function in the face of material and associated constraints and recalcitrances. Furthermore, their materiality is associated with model-understanding as well, namely, in that working on their design implies a model-based understanding of their make-up as system *and* of their functionality.

The multiplicity of model-based understandings implicated in a model system implies that not all of its aspects need to be or even can be simultaneously under scrutiny in the research process. The following quote may serve as an eloquent illustration of scrutiny pertaining to the set-up and functionality of the flow-loop device in Lab A; it is taken from an interview with a former graduate student, now a successful faculty member at another institution(emphasis added to the original quote):

> A23: So um, when I got here in 1994 uh, the flow chamber was a mess. It was a benchtop system, it had bulky tubes that looked something *like some time machine from the 1950s or something* […]. Um, but anyway it was quite messy and you know culture studies have to be done at 37 degrees so the way that they would do this was you know, incubators were certainly around in 1994, uh, they would wrap these coils, these heating coils around these glass reservoirs and because it had to be a set flow, they would use a hydrostatic pressure difference to derive the flow, and uh, a clamp, a regulated clamp to try and regulate the flow through the chamber and out into the uh, into the rese-the lower reservoir. So you had two reservoirs, one at the top, and one at the bottom, there'd be a hydrostatic

difference between them, and then things would flow and then this whole thing would be sitting on the benchtop uh, big bulky glass reservoirs with bulky tubing and um,[…] And this was subject to about a 50% success rate.

Interviewer: In terms of contamination?

A23: In terms of contamination. And the reason was because this whole thing had to be assembled outside of the hood [colloquial for 'the sterile workbench']. There was no way you could assemble this thing to stand up-this thing was on stands--you have to assemble this part outside of the hood, so basically they we would connect these joints here, and connect them outside of the hood. […] Doing experiments longer than 48 hours was almost impossible, because at experiments longer than 48 hours the incidence of contamination was probably greater than 90%. Um, but that wasn't really the motivating factor for why I considered changing this design. I actually went to an internship in the first summer that I was here. […] So they [referring to the lab at which he interned] preferred as opposed to heating things, having everything in the incubator. And so when I came back from that internship, the uh I really like compact designs and I'm always looking for ways-maybe I'm Japanese in that way, I don't know […]. So when I came back from [the internship], I uh, I instituted a lot of the things I saw over there and in our laboratory, and one of the things was *model-revising this design* to go into the incubator. And uh, that was really why we moved from a system that required heating coils and an upper reservoir and a lower reservoir to a system that was just flow driven with a peristaltic pump and a pulse dampener

> that was-and everything could be done inside the incubator with smaller tubing, little reservoirs as opposed to big reservoirs.

"Model-revising this design" as the former graduate student described his contribution to this line of research meant to re-design the *physical system* that is the flow channel device, its parts (e.g., the reservoirs, the tubing), its set-up (e.g. on stands in the lab vs. compact and in the incubator) and the physical principles governing its functional design (e.g. hydrostatic pressure difference vs. integration of a peristaltic pump). The actual flow channel, that is the part where cell cultures are flowed is but one component in the set-up that functions as the model system, and, in fact, was left untouched in this particular re-design. Thus, re-engineering this design, in this case, did not involve those parts where the cells-in culture or the constructs (as 'wet' devices) interface with the mechanical device. But, of course, re-engineering this design had everything to do with its function as part of a model system, which is practically completely dependent on its resistance to contamination of the involved cell cultures. For the engineer, the set-up that functions as the model system is sufficiently decomposable to allow for the re-engineering of its varied model-based components partaking in this particular set of *interlocking models*.

Many instances of model-based reasoning in science and engineering employ 'external' representations that are constructed during the reasoning process, such as diagrams, sketches, and physical models. These can be seen to provide constraints and affordances essential to problem solving that augment those available in whatever 'internal' representations are used by the person during the process. In this way, 'cognitive capabilities' are understood to encompass more than "natural" capabilities.

The devices used in Lab A are *physical models* employed in the problem solving. Within the cognitive systems in the lab, then, devices instantiate part of the current community model of the phenomena and allow simulation and manipulation. The intent of the simulation is to create new situations *in vitro* that parallel potential *in vivo* situations (where, as discussed above, this parallelism is a 'situated' historical process). In previous research Nersessian (1999, 2002b) characterized the reasoning involved in simulative model-based reasoning as a form of dynamic mental modeling. In that analysis the focus was on thought experiments and tied the internal processes of mental modeling to narratives. In this research, we expand the notion of simulating a mental model to comprise physical, non-linguistic, models as well as what are customarily held to be the internal thought processes of the human agent. Simulative model-based reasoning in these cases then involves a novel division of labor, in that physical, non-symbolic models are enlisted as cognitive agents.[18] This assignment is possible for model systems because the researchers intend them as epistemic artifacts (see Tweney 2002). Thus, although physical simulations with these model systems are implemented externally relative to the researcher's body, they nevertheless are integral to the researchers' mental model by being intended to function epistemically. Thus, for a model to carry the attribute *mental* would more nearly describe its generative quality, i.e., the quality that insight or inference is intended to flow from it (however, intricate, culturally and socially mediated their generation in fact may be), rather than its locus or medium of operation.[19]

[18] By using "novel" we do not mean to imply here that the use of such model systems is a historically new occurrence (see Jackson 2001).

3.4. From model system to a 'fabric of interlocking models'

Models tend to come in clusters or configurations, that is, not as isolated entities but rather as standing in particular relationships to other models. A productive understanding of the interlocking of models depends, at least, to a certain extent on the construction, trading, maintenance, and possibly critique of particular historical understandings, which bind the models together not only in a narrative but in the practiced 'lore' that is rehearsed in a configuration of practices—among them discursive, iconic, computational, material, methodological, social, and most generally cultural practices. For instance, Kurz-Milcke and Martignon (2002) have analyzed a particular set of modeling practices in psychology which relate a certain iconic model (first proposed by the psychologist Egon Brunswik) with certain mathematical and computational models, which were again associated with certain (normative) models of experimental methodology in psychology.[20] We conjecture that the set of interlocking models in a research area and/or in a lab is simultaneously a point of stability *and* departure for its research activity. Thus, we conceptualize these sets as evolving, with novel elements and models being integrated with them, and others lost from them as the research progresses. We picture this process as resulting in *a fabric of interlocking models*. Through this 'fabric' extended developments in technology and methodology have a 'situated' presence in the lab and thus can function as resources for further developments and for their justification. In the labs' daily workings this presence is inextricably coupled with the social networks of the

[19] For related attempts to reconceive mental modeling, see (Greeno 1989) on the relation between mental and physical models in learning physics and (Gorman 1997) on the relation between mental models and mechanical representations in technological innovation.

[20] This latter notion of a model has been developed in Danziger (1990), where it denotes the social relationships and practices embedded in experimental methodology in the field of psychology.

labs, which equally extend into the labs' recent and not so recent past depending on who is involved.

With the following narrative we seek to convey a taste of such a 'fabric' for the case of Lab A. Ours is a narrative by outsiders, of course. In the lab's dealings the fabric of interlocking models is not primarily present or even relevant in the form of a single narrative but rather distributed among and situated with various settings, research projects, objects, social networks, and communications occurring in relation to all of the aforementioned. Our narrative pertaining to Lab A is based on various sources including publications[21] and interviews. As an *organizational unit* within a larger research institute, Lab A was founded in 1986. Research- and agenda-wise, it has a prehistory in the PI's research after his engineering interests moved in the direction of biology. We give a brief description of this stage setting and hint at some of the subsequent developments in Lab A. Some of the devices and models in Lab A were part of the research that the PI carried out prior to establishing Lab A. The configuration of interlocking models that the PI brought with him to his new lab set the stage for the lab's research agenda and in relation with efforts by others was to a certain extent formative for the emerging interdiscipline of BME.

Early experimentation in bioengineering as it relates to the vascular system was conducted by the PI and colleagues on blood vessels that were altered while in the living organism. Through surgical interventions blood vessels were made to exhibit pathological conditions consisting in narrowings of native arteries (stenosis). After sacrificing these animals the morphology of the cells lining the arterial walls at the

[21] Confidentiality for the lab members does not allow us to identify the published materials on which we have drawn or from which we are quoting, as would be standard with a historical account.

pathologically altered regions was studied and quantified in particular aspects (e.g., elongation, and orientation of cell filaments). Simultaneously, arterial flow patterns (velocity profiles) were studied for these pathological narrowings with models replicating the *geometrical dimensions* of these pathological regions. These *replica models* were achieved through casting techniques in which vessels were filled with a fluid plastic and after hardening were used as casts to manufacture replica of the narrowed arterial vessel. These replica models, individual instances of which were referred to as "the model," were studied in experimental set-ups that allowed "flow studies" using laser doppler studies to determine velocity patterns with these replica models. The results gained from studying cell morphology and from studying velocity patterns in the replica vessel were *correlated* to gain insights into the relation existing between variations in wall shear stress due to particular velocity patterns (gradients near the vessel wall) and cell morphology of cells lining these vessels. The association of research practices from engineering with practices from biology in this research paradigm was the beginning of the extended network of interlocking models that would later characterize the workings of Lab A. However, the elaborate material and measurement practices related to these replica models were merely a beginning and fairly quickly abandoned by the PI and his collaborators at the time. Not so, the program of studying the impact of flow in wall shear stresses with engineered devices.

Simultaneously with the described "replica" studies and its associated cell morphology studies, the PI and others had started a line of research with *cell cultures* of the endothelial cells typically lining the arterial walls. Instead of inducing stenosis in living animals (which in itself was a rather involved project, to say the least) and thus

creating particular flow patterns resulting in particular wall shear stresses, they now exposed the respective cell type *in culture* to wall shear stresses by "flowing" them in *a flow channel*. These *in vitro* experiments on the cells' response to shear stresses were based on an established fluid dynamic model, specifically, the fluid mechanics of a "long channel with rectangular cross-section," which from a mathematical point of view are considered to be known. In this way, changes in cell morphology (elongation and orientation) could be directly related to known wall shear stresses. Furthermore, the measurement of velocity patterns in a replica model was now paralleled by an engineered artifact of exact geometrical specification, a flow channel. With this 'well-behaved' flow channel the correspondence between the mathematical and the physical model (otherwise, the replica model) had become an issue of the engineering of a channel with the appropriate dimensions (being in a physiologically meaningful range), and no longer subject to measurement of velocity patterns using elaborate laser doppler technology.

The PI of Lab A summarized for us this earlier period, prior to establishing the practices of the lab in their current 'in vitro' form, by saying that it "moved [the research] from animal studies to cell culture." In this line of research an engineered artifact, a flow channel with the accompanying flow-inducing components, became a *parallel* situation to *in vivo* conditions of blood vessel pathology (induced) in living organisms. The studies using the replica model had in fact dissociated the *study of* cell morphology from the *study of* flow patterns, *correlating* their results after the fact. With the "channel flow device" the two foci of study were condensed into a single device, in which cultured cells were exposed to flow and thus shear of a well-defined nature. The *channel flow device* thus reconfigured the study of vascular pathologies relative to the in vivo occurring

phenomena related to blood vessel stenosis and also relative to previous studies of these phenomena based on the combined but separate study of cell morphology and flow patterns (with the replica model). Subsequently designed devices emulated other aspects of the vascular system. One fairly consequential innovation in the lab was the development of *tubular* constructs as models of the material composition of blood vessels and especially the arrangement of various cell types within them.

Notably, the move towards a tubular shape for the constructs and thus a shape more closely mimicking the shape of blood vessels was immediately accompanied by the inception of still another device, the bioreactor (see Figure 3). The biorector emulates the forces due to pulsatile distension, which appears important once an artificial vessels became introduced to the lab that was materially more closely related to a native vessel by allowing for distension than was the 'well-behaved' and sturdy flow channel used with the flow loop device. In the words of a lab member who was involved in these developments:

> A23: Uh, when I got here, [the PI] told me that he was interested in getting these guys here—these blood vessel constructs in a tubular shape. Uh, I think before that we were making them in a slab. And uh, we wanted to go to a tubular shape for obvious reasons, I mean these were supposed to be blood vessel constructs. And uh, so my job was to first of all move us out of these slab studies and into tubular studies. And more so trying to understand how we can apply physical forces onto these tubular constructs so as to stimulate the cells inside of there, namely the smooth muscles, but also endothelial cells. Uh, to reorganize, just to

> appreciate their surroundings, you know the problem with a lot of these studies, these tissue engineered blood vessel studies is that they reside in static environment and [the PI] says that static environment is very artificial for any kind of human cell or living cell. Most of our cells reside in a dynamic environment and so the objective was to be able to do that.

One model system and device has led to another, in the process evolving the fabric of interlocking models that contributes in major ways to shaping the lab's agenda, its research and social practices, and its material culture. Through this fabric of interlocking models both provinces, in vitro and in vivo, are reconfigured in specific ways; these reconfigurations are conditioned on the entire fabric of interlocking models. BME researchers are called to master fabrics of this kind; not in all its detail and practices, but to a considerable degree, not as individuals but as a lab members, and not in the abstract but hands-on with the devices in the lab. This 'fabric' relates and delineates a lab's evolving distributed cognitive systems for its members.

4. Discussion: What--in the lab--has history to do with cognition?

Participating in the epistemic culture of the BME lab involves developing a sense for, and subsequently expertise in, the fabric of interlocking models in this research area. In the BME lab, this fabric relates signature artifacts, to each other and to the lab agenda, which typically involves the design of bioengineered devices for medical application. To fulfill this agenda, bioengineered devices (e.g., the blood vessel construct) are experimented with and on, and tested with other devices, that are specifically engineered for this

purpose (e.g., the flow loop, the bioreactor). Thus, on the surface of it lies a very simple insight, which will hardly surprise, that the physical objects unique to a research area and possibly a lab have a purpose and are related through their purposes to the larger problem that the lab is working to address. This insight might be cast as a lab tour (not an uncommon occurrence with these laboratories), in which a lab member guides a group of visitors through the lab pointing out the spaces, instruments and devices and giving a general overview to the lab's work and agenda. Here is a constructed snippet to illustrate: "…and here you see a bioreactor, which we use to exercise our cells to form stronger constructs, which are our artificial blood vessels that I showed you a minute ago, and this student sitting at the hood, is assembling a flow loop, which we use to flow our blood vessel constructs which helps us to better understand how flow patterns influence the cells on these constructs and in our vascular system…" Such a tour can be impressive but is, of course, a far cry from letting the casual visitor in on the lab as a research unit. The reason is not secretiveness on the part of the lab members. Knorr Cetina (1999, p. 21) has described this non-secretive attitude well for the physicists in her ethnographic studies as stemming from an "affirmation of the openness and public character of everything they do." Rather, we argue here that the fabric that carries most weight in these laboratories is to a substantial extent beyond narration by being of the nature of interlocking models.

Being beyond narration, however, does not mean that this fabric is also beyond history, or that it is independent of narratives and linguistic structures and categories--quite to the contrary. Prospective newcomers to the lab or newcomers on their first day in the lab are often given a tour not unlike the one hinted at above. Pretty soon, however, they start to get involved, hands-on, with the engineered and biological artifacts in the

lab, which eventually draws them into the field of multi-referentiality of these artifacts. It is easy to see that a tubular construct somehow is like a blood vessel, even understanding its layered composition consisting of various materials and cell types is still relatively straightforward. Changing this composition, however, and studying its properties is involved and intricate. This latter part, of course, is what the work is all about. Finding ways and being skilled enough to change the composition of a blood vessel construct leads into reasoning about these constructs in ways that goes distinctly beyond their composition in terms of layers. At this point, cells and the tissue they form become agents, and as we like to put it *partners* to the researcher in their quest to arrive at better designs. Re-design of devices in the lab is embedded in the formation of problem understanding, that is, the understanding how a certain problem situation has led to the realization of certain design options. In other words, the scientific agenda of re-design characteristic of an engineering laboratory *historicizes everything*. The current design is understood to be conditioned on the *problem situation* as it existed for the lab, i.e., the resources that were available at the time of the respective design's inception and further development, even if these resources and parameters are not fully known to the current researchers. The same holds for the problem that the current design addresses which is perceived as being equally conditioned on this problem situation. Thus, re-design implies constructive and creative involvement with the *historicity of design*, in fact, the material culture of these labs is such that it is unmistakably apparent that there is no ridding of constraints, only shifting to novel ones.

History then is not merely a process (no matter how culturally rich) that moves us from time 1 to time 2, and at 2 lets us look back at 1. At least, this is not the only or even

most relevant notion of history implicated in the scientific practices of these bioengineering laboratories, although on the face of it 'design and re-design' seems to be well captured by a t_1-t_2 pattern. What needs to be figured into the analysis is the strict focus on innovation in the epistemic culture of the BME lab. *Redesign is agenda* and with it the historicity of the artifacts becomes a *resource* for novel design options. In practice, the historicity of a device or model system is not an easily accessible resource. We have seen undergraduate researchers carrying out their projects with hardly any understanding of the historicity of particular designs. The task as it presented itself to them was strictly one of rehearsing what others had done before, which of course can create its own difficulties and in this way can in turn play out as a pointer toward the historicity of the design (see Nersessian, Kurz-Milcke, & Davies, under review). Tapping historicity as a resource requires a holistic conceptualization of the lab's workings, in other words, the lab-as-problem space. Simultaneously, identification with the engineering component functions like a 'permission slip' to tap that resource. In the context of the BME lab, the affordances are such that recognition of the historicity of the problem, of the design process, and of its outcome is only of importance if it is intellectually hands-on, that is, can be meaningfully related to working with the respective devices.

With this paper we have sought to substantiate our claim that simulative model-based reasoning happens on, at, and in conjunction with the benchtop in the BME laboratory. Devices, wet and other, as "controlled [experimental] environments" and as simulators are conjoined in model systems enlisting biological systems for design purposes. We have introduced the notion of interlocking models in order to indicate how devices and, consequently, model systems in these labs are multi-referential: their

simulative intent and function pointing toward biological understandings and systems, their make-up and composition toward engineered systems and structures, and their participation in biological research toward experimental control and exploration. Devices and models systems thus rely on a variety of models and model understandings, and ways to meaningfully relate these to each other. The particulars of the respective interlockings of models leaves room for research domain-specific, lab-specific, project-specific and lab member-specific preferences with respect to the emphasis and detail that is given to particular models and relations among models. In their evolution these interlockings of models are better understood as forming a fabric of interlocking models, and we have sought to indicate how each lab weaves its fabric or portion of such a fabric and also how this fabric relates to the social network and research agenda in a lab, all of the aforementioned evolving, of course. In this way, model-based reasoning as formation, maintenance and selective expansion of simulative capabilities in the lab is distributed across a fabric of interlocking models. We can meaningfully isolate particular threads in this fabric or portions of this fabric, the lab members themselves engage in both. In the end, however, the lab trains one to apprehend the fabric.

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Figure Captions

Figure 1. Photograph of several artificial blood vessel *constructs* as designed, manufactured, and researched in tissue-engineering Lab A. These *constructs* are designed from various cell types typical of the vascular system and a collagen component (or matrix). The *constructs* are cultured on glass mandrills, and here shown in a closed culturing dish. The lids of culturing dishes are typically labeled with a marker (see the glass top of the dish in this photograph) to indicate date of manufacture, cell types and other information about their specific design and materials.

Figure 2. Diagram and photograph of a laminar flow chamber, known as *flow loop* in tissue engineering Lab A. The *flow loop* as known by Lab A is assembled from various parts by the lab members and used to expose cell cultures to well-controlled flow and the respective shear stresses. After assembly at the sterile workbench, *flow loops* are operated in an incubator to provide the cells-in-culture with the appropriate conditions.

Figure 3. Photograph of a *bioreactor* as it is known in tissue-engineering laboratory, Lab A. This *bioreactor* is used to distend artificial blood vessel *constructs* to stimulate and research the cells that are cultured on the outside of prepared silicon sleeves. The sleeves with constructs are sutured onto mandrils inside the bioreactor's reservoir. The reservoir is filled with red culturing medium, as is the inside of the sleeves. The medium is forced into the sleeves by a pump to create well-calibrated pulsatile distension.