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CHAPTER 35

Interdisciplinarity in Engineering Research and Learning

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> Disciplines are distinguished partly for historical reasons and reasons of administrative convenience (such as the organization of teaching and appointments) and partly because the theories which we construct to solve our problems have a tendency to grow into unified systems. But all this classification and distinction is a comparatively unimportant and superficial affair. We are not students of the same subject matter but students of problems. And problems may cut right across the border of any subject matter or discipline.
>
> Sir Karl Popper Conjectures and Refutations (Popper, 1962, p. 67)

Introduction

Moves beyond disciplinary thought and practice abound today. National and international funding agencies are creating, facilitating, fostering boundary crossing and cross-disciplinary synergy and integration as a focal point of their agendas across the sciences, medicine, engineering, humanities, and arts. Research on interdisciplinarity (ID) as it is practiced in humanities and the sciences is also abundant, ranging from rich case studies of specific instances to bibliometric analyses that aim to map such things as patterns of interaction in scientific fields. To date, however, the research on ID as practiced in engineering fields is scant, both with respect to practice and to education.[1] Yet, as noted in the National Academy of Engineering (NAE) report on the engineer of 2020, the demands of twenty-first century engineering are such that education needs to be redefined starting at the undergraduate level:

> *The dissolution of boundaries between disciplines such that 'imagination, diversity and capacity to adapt quickly have become essential qualities for both institutions and individuals, not only to facilitate research, but also to ensure immediate and broad-based application of research results related to the environment. To meet these complex challenges as well as urgent human needs, we need to . . . frame integrated interdisciplinary research questions and activities to merge data, approaches, and ideas across spatial,*

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> *temporal and societal scales. (NAE, 2005, p. 36, quoting AC-ERE, 2003)*

In this chapter we focus primarily on ID as it is enacted in engineering research laboratories. Our focus on practice stems from what we call a *translational approach* to transforming engineering education, by which education researchers first investigate the cognitive strategies and learning ecologies as they occur in the practices of a specific field and then translate findings from these investigations into instructional environments using design-based research. This approach infuses the actuality of the cognitive and learning practices found in the engineering workplace into the classroom setting. The goal is to achieve greater parity between the synthetic environment of the classroom (*in vitro)* and the authentic environment outside the classroom (*in vivo*) (Newstetter, Behravesh, Nersessian, & Fasse, 2010). As with Popper's claim earlier, our research supports the position that ID in engineering is *problem-driven*, and, further, that the nature of the problems and the variety of approaches to them require that we differentiate among different kinds of ID practices. A recent National Academies report defines ID as "a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice" (NAS, NAE, & IM, 2005, p. 26). What is powerful about this statement is that it goes beyond the usual focus on language and communication to highlight the numerous dimensions across which ID integration needs to take place. However, although there is recognition in the literature on ID that there are several forms, policy statements such as this tend to treat it as though it were all of one kind. As developed in later sections, our research supports the need for a more nuanced understanding of the varieties of ID fields, which can be characterized as *multidiscipline*, *interdiscipline*, and *transdiscipline*. In this chapter, each is exemplified with specific cases from engineering.

The structure of the chapter is as follows. Before beginning the analysis that derives from our *in situ* investigations of ID, we begin with a brief survey of the landscape of the main conceptual understandings of ID to provide readers with entre to the literature on ID broadly construed. We then draw on analyses of ID processes in the science studies literature and in our own research to provide some analytic tools for thinking about ID in practice. We then focus on what ID looks like in action by considering the variety of ID in engineering practice, and conclude with implications for learning in engineering education.

Tools for Analyzing Interdisciplinarity

The characterization of ID by the leading contemporary scholar in the field, Julie Klein, resonates with the sentiment expressed nearly thirty years earlier by Popper (see earlier):

> *Interdisciplinarity has been variously defined in this century: as a methodology, a concept, a process, a way of thinking, a philosophy, and a reflexive ideology. It has been linked with attempts to expose the dangers of fragmentation, to reestablish old connections, to explore emerging relations, and to create new subjects adequate to handle our practical and conceptual needs. Cutting across all these theories is a recurring idea, interdisciplinarity is a means of solving problems and answering questions that cannot be satisfactorily addressed using single methods or approaches. (Klein, 1990, p. 196)*

Thus, ID is best understood as a *process* (Klein & Newell, 1996) of problem solving, and there is widespread agreement that the hallmark of ID processes is *integration* (Klein, 1990, 1996; Lattuca, 2001; NAS, NAE, & IM, 2005). Much of the focus of research on ID has been on collaboration in ID teams comprising members coming from different

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disciplines (see Derry, Schunn, & Gernsbacher, 2005 for a number of case studies), a practice for which, according to Klein (Klein, 2005) World War II was a "watershed" (see also Galison, 1997). Given the focus on integration in most research on ID, *multidisciplinarity* is most often contrasted with *interdisciplinarity* because it is argued to fail to achieve lasting integration of disciplinary components. Individuals come together from different disciplines, work together on a problem, and then return to their disciplinary habits and abodes largely unchanged. The other less widely recognized form of ID is *transdisciplinarity*, which is variously construed in the literature as *trans*cending disciplinary boundaries through a kind of overarching synthesis toward the pursuit of applications (Klein, 2010). Some have also suggested that transdisciplinarity invites a broader range of stakeholders from the public or practitioners recruited to solve an authentic problem (Borrego & Cutler, 2010). In the discussion that follows, we address all three kinds of ID while trying to distinguish to the extent possible among them.

Disciplinary research is often characterized as taking place in "silos" and interdisciplinarity, as moves out of these. How are these moves made? What facilitates interaction and integration? What are the characteristics of the interactions and integrations? Here we introduce some metaphors in the science studies literature on interdisciplinarity that we have found to be useful for articulating and analyzing these dimensions.

Trading Zones

In characterizing the development of microphysics by experimentalists, theorists, engineers, and mathematicians, spurred by various problems that fueled research and development during World War II, historian Peter Galison sought a metaphor that would capture the movement and interactions across boundaries that occurred within these cultures. He called the process he was trying to capture~~,~~ "intercalation": coordination without homogenization and used the metaphor of "trading zone" to colorfully capture this concept. He found the trading zone metaphor in the thinking of anthropologists and linguists about how communication and exchange of goods of value can take place among radically different communities with no cultural point of reference or language:

> *Two groups can agree on the rules of exchange even if they ascribe utterly different significance to the objects being exchanged; they may even disagree on the meaning of the exchange process itself. Nonetheless, the trading practices can hammer out a local coordination, despite vast global differences. In an even more sophisticated way, cultures in action frequently establish contact languages, systems of discourse that can vary from the most function-specific jargons, through semi-specific pidgins, to full-fledged creoles. (Galison, 1997, pp. 782–783)*

The notion of a *trading zone* designates a bounded, delimited space in between disciplines where trading processes can occur because each participant group needs something from the other to address problems that lead to shared projects and goals. In his analysis of the trading zones, "language" is expanded to mean any structured symbolic system, which can include graphical and mathematical representations. The central metaphor is *exchange*: researchers come together for a period and exchanges take place, and then everyone goes back to where they came from. It is possible that fundamentally new concepts and techniques emerge in the zones that then impact the original disciplines as in the case of Julian Schwinger discussed later. Schwinger took back some of the "pidgin" of the MIT Radiation Lab and used it to great effect. However, emergent disciplines are not the focus of Galison's interpretations, and as we discuss later, trading is not the best metaphor for these. The main point is that transactions take place within the trading zone and everyone goes back to their disciplinary silos, with the disciplines largely unchanged although occasionally individuals have significant impact on their disciplines from this cross-cultural encounter.

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Boundary Objects

In their study of how workers at the Museum of Vertebrate Zoology (curators, amateur collectors, professional biologists, occasional field hands, science club members) managed both diversity and cooperation, sociologist Susan Leigh Star and philosopher James Griesemer introduced a notion that has had wide impact on studies of interdisciplinarity: *boundary object*. The example they use is specimens of dead birds which had differing meanings for the intersecting worlds of amateur bird watchers and professional biologists in the context of various problems involved in museum work. They designated as boundary objects:

> *. . . those scientific objects which both inhabit several intersecting social worlds . . . and satisfy the informational needs of each of them. Boundary objects are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual use. These objects may be abstract or concrete. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable as a means of translation. (Star & Griesemer, 1989, p. 391)*

A boundary object is an entity (concrete or abstract) that has a complex structure such that it is compatible with more than one interpretation. Parts of that structure meaningfully intersect across the communities concerned with it. The notion of a *boundary object* has been extended to a wide range of instances in the subsequent literature, such as the everglades (conservation science: scientists of various kinds, environmentalists, government agents), soil (soil science: geologists and botanists), hand-drawn sketches; engineers and architects and cloud chamber traces (particle physics: experimentalists, theorists, instrument makers).

An object or entity is a static notion but one thing boundary objects can do is to lead to the construction of spaces of dynamic interaction between disciplines, which is how Galison characterizes the trading zone. Thinking about how new spaces can lead to the emergence of ID engineering fields has led our research group to introduce the notion of *adaptive problem spaces* where disciplines intersect and hybridization and other forms of emergence occur. Further, we introduce the notion of *boundary agents* to capture agency of participants in constructing these ID spaces.

Adaptive Spaces and Boundary Agents

Whereas zones and objects are bounded in that they are delimited or constrained spatially and temporally we think of adaptive problem spaces as finite but unbounded spaces (on analogy with the Einsteinian conception of the physical space of the universe) where problem-driven adaptation takes place in a complex system. In our work, we have come to formulate the notion of adaptive spaces as follows:

> *Adaptation of complex systems is a process of continually revising and reconfiguring the components from which these are built, as these gain experience. Research in adaptive spaces is driven by complex interdisciplinary problems, and these require that the individuals themselves achieve a measure of interdisciplinary integration in methods, concepts, models, materials – in how they think and how they act. Adaptive spaces are distributed in space and time. They are dynamic and diachronic and span mental and material worlds. (Nersessian, 2006)*

Unlike the inhabitants of trading zones who return to their disciplines after working on a problem, researchers and artifacts within the adaptive space become to varying extents hybrid systems and inhabit regions that can themselves give rise to new hybrid disciplines (interdisciplines such a biomedical engineering) or can be more varied (transdisciplines such as integrative systems biology). Although the central metaphor of a trading zone is exchange, the central metaphor of an adaptive space is *emergence*. The people who are forging the adaptive space to advance the processes of interdisciplinary

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emergence through their activities we designate as *boundary agents*.

The literature on ID has tended to focus more on integration of language, methods, theories, and so forth, with less attention directed toward the individuals who do the integration and the ways ID impacts them as researchers. Understanding the kinds of adaptations and transformations researchers need to undergo to become boundary agents raises issues of cognitive development through learning, identity, and the development of interactional skills suited to the variety of ID practice. The latter skills have been called *interactional expertise* by the sociologist Harry Collins (Collins & Evans, 2002). Although his use of the term focuses on the idea that participants in ID work need, to some extent, to learn the languages of the other discipline(s), we expand the notion to comprise other facets of ID interaction.

Interdisciplinary Engineering in Action

Our research has led us to classify varieties of ID practice in terms of the kinds of engineering these have been producing. In this section we provide examples of ID engineering in research laboratories for each of the varieties: *multidiscipline*, *interdiscipline*, and *transdiscipline*. In a multidiscipline, participants from disciplines come together in response to a problem, create a local integration to solve that problem, and go back to their respective disciplines, with these largely unchanged by the *transient* interaction. In contrast to the current ID literature surveyed in the preceding text, we cast such multidisciplinary interactions as falling within the category of ID research because problem solutions do require and achieve integration, even if the disciplines themselves are largely not impacted. We have not investigated this form of ID ourselves, but use an interesting historical case as illustration: microwave engineering research within the MIT Rad Lab in which engineers and physicists collaborated on the problem of radar development in World War II.

In our investigations of engineering research laboratories, we have found that an interdiscipline might be thought of as a *hybrid discipline* – one that emerges when the integrative activities of participants move beyond collaboration to create a new hybrid field in which there is *stable and sustainable integration* in concepts, methods, technologies, and materials in the service of addressing an ongoing range of problems. We use biomedical engineering as an exemplar.

The notion of a transdiscipline is harder to articulate, but the basic idea is that researchers draw largely on the knowledge, methods, etc. of a discipline, but address problems that require *penetration* by one or more other disciplines. That is, interactions are likely to mutually effect changes in understanding, methods, and other practices in regions of the participating disciplines that seep into the adaptive space. The case we look at here is integrative systems biology, which involves ~~interactions~~ among researchers in engineering, computing, and biosciences. In this context, the prefix "trans" signifies that this enterprise seeps into, penetrates, specific prior practices of the mother fields and a further emergent problem space opens with multiple possibilities for interaction and integration.

Multidiscipline: Microwave Engineering in the MIT Rad Lab in World War II

This exemplar provides an instance of ID collaboration that was driven by a problem external to the communities and the collaboration was pragmatic and expedient. The problem of creating radar systems for the war effort brought electrical engineers and theoretical physicists together in what came to be known as the MIT Rad Lab. We provide only a brief account because our discussion relies on secondary sources. As Galison analyzes the interactions in the trading zones between physics and engineering, the main interdisciplinary problem was one of translation of the complex mathematics of

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electromagnetic field theory into a form electrical engineers, accustomed to algebra and circuit language, could understand and use to analyze wave guides, which are long, hollow metal boxes with discontinuities (Galison, 1997). Electrical engineers were by-and-large not familiar with the mathematics of field theory and even for the physicists, the usual method of solving the electromagnetic field equations for all points in the field proved an intractable problem. The physicist Julian Schwinger developed a mathematical notion of "equivalent circuits." Reducing complex electromagnetic field representations to circuit representations with which electrical engineers were familiar greatly simplified the calculations required and enabled the engineers to predict various aspects significant to radar design in advance of constructing the artifact. Thus, exchange was affected by means of simplified diagrammatic representations and equations, which performed as boundary objects, equally meaningful to the physicists and the engineers.

The exchange led to the development of radar, and with success in the trading zone everyone then went back to their disciplinary silos. However, the exchange process also had a significant impact on the thinking of the person we would call the boundary agent, Julian Schwinger. As Galison details, not only did Schwinger's methodological and conceptual innovation figure centrally in the development of radar, but when he left the zone and went back to particle physics he had a new way of thinking that ultimately led to his notion of renormalization in quantum electrodynamics. That is, in developing interactional expertise in electrical engineering, Schwinger also developed a mode of thinking about complex phenomena in terms of minimal structural aspects. Schwinger himself linked the seemingly unrelated domains of radar and QE~~E~~D in a memorial lecture for the Japanese physicist Tomonaga: "The waveguide investigations showed the utility of organizing a theory to isolate those inner structural aspects that are not probed under the given experimental circumstances.... And it is this viewpoint that [led me] to the quantum electrodynamics concept of self-consistent subtraction or renormalization" (Galison, 1997, p. 826).

Interdiscipline: Biomedical Engineering Research Labs

This exemplar is drawn from our eight-year study of cognitive and learning practices in research laboratories in biomedical engineering (BME). In this case the interdisciplinarity is explicit, reflective, and intentional, with the ultimate aim of stabilizing into an "interdisciplinary discipline" or interdiscipline. Pioneering engineers in the field wanted to move beyond multidisciplinary collaborations to creating the *integrative individual* biomedical engineer. Researchers believe the challenge of biomedical engineering now and in the future to be that the research problems are inherently interdisciplinary, calling for the integration of concepts, methods, materials, models, and so forth into *emergent hybrid systems* within the adaptive problem space of BME. The cases we have examined in some depth come from tissue engineering and neural engineering. Here we discuss salient interdiscipline features these labs have in common and then provide some brief details of a hybrid researcher in tissue engineering.

The BME labs are hybrid engineering and biological science environments. The hybrid nature of these laboratories is reflected in the bioengineered physical simulation model-systems designed, built, and experimented with by the labs. This hybridity is also found in the characteristics of the researcher-students who are part of an educational program designed explicitly to produce individuals who are interdisciplinary, integrative biomedical engineers who can also act in industry and in academia as boundary agents in interaction with collaborators from any of the three disciplines. Research in biomedical engineering often confronts the problem that it is both impractical and unethical to carry out experiments directly on animals or human subjects. In our studies of two pioneering biomedical engineering research laboratories we have found a

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common investigative practice is to design, build, and experiment by means of *in vitro* systems, which parallel certain features of *in vivo* systems. When biological and engineering components are brought together in an investigation, researchers refer to this as a "model-system." As one respondent stated: "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 coming together with an engineering aspect . . . " These physical models are hybrid artifacts engineered to capture what researchers deem to be salient properties and behaviors of biological systems (Nersessian & Patton, 2009). They are structural, behavioral, or functional analogs of *in vivo* biological phenomena of interest with engineering constraints that impose simplifications and idealizations unrelated to the biological systems they model. These emergent hybrid objects are not boundary objects, but are integrated artifacts understood in the same way by the community of researchers.

Lab A, in tissue engineering, seeks to design off-the-shelf vascular tissue replacements for the human cardiovascular system. Some intermediate problems that drive the research are: producing "constructs" (blood vessel wall models composed of living tissue that mimic properties of natural vessels); examining and enhancing their mechanical properties; and creating endothelial cell sources through mechanical manipulation of stem cells. Lab D, in neural engineering, seeks to understand the ways neurons learn in the brain and, potentially, to create aids for neurological disabilities. Its intermediate investigations center on finding evidence of plasticity in a "dish" of multi-electrode neuron arrays, and producing controlled "muscle" activity in robots or in simulated agents, all of which constitute their model-systems. Given space constraints we can consider only a brief example from one lab, tissue engineering, which illustrates its nature as an adaptive space in which hybrid BME researchers and artifacts emerge.

Research in Lab A stems from the insight its director had in the early 1970s: "characteristics of blood flow [mechanical forces] actually were influencing the biology of the wall of a blood vessel. And even more than that. . . . 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 [endothelial] had to be involved." The central problem became that of understanding the nature of these influences of mechanical force on the vascular biology, codified in the hybrid concept arterial shear: frictional force of blood flow parallel to the plane of flow through the lumen. Lab research is directed toward both fundamental problems, such as of endothelial cell biology, and potential application problems, such as engineering a viable artery substitute. Tackling these problems had led to the development of a number of hybrid model-systems. The processes of creating and using models drive researchers to be integrative interdisciplinary individuals. The design of model-systems incorporates engineering and biological constraints, making them hybrid objects used to simulate the in vivo phenomena of interest and provide sites of experimentation.

The construct model (see earlier) is now the central focus of research in Lab A. The nature of the model changes along various dimensions depending on the constraints of the experiment in which it will be used. For instance, it can be seeded with smooth muscle cells and endothelial cells, or simply the latter, and the components of the collagen scaffolding can vary. At any given time, its design is based on what is currently understood of the biological environment of endothelial cells in cell and vascular biology, the kinds of materials available, and bioengineering techniques thus far developed. Building the construct has led to new hybrid methods for the engineering of living tissue. Once built, a specific construct model can be manipulated by various means as part of an engineered model-system. One form of manipulation is by the flow channel device ("flow loop"), an engineered model of the *in vivo* force of blood flow over the lumen.

The flow loop design is based on the fluid mechanics of a long channel with a rectangular cross-section. Exposing the endothelial cells lining the construct to shear stresses "conditions" the cells, and can be the locus of experiment itself (e.g., relating to cell morphology or gene expression), or just one step in a multi-model process.

A diagram, drawn by the Lab A director in response to our request that he "draw a picture" of the research in his lab, provides a glimpse into the dimensions of the adaptive space of Lab A (Figure 35.1). He mapped not only the problems ("major barriers"), but also the technologies (at the bottom), the relations of researchers to both of these and to one another in that space. This map begins to articulate an adaptive space distributed across problems, methods, technologies, and members; as well as connecting the lab to resources and communities external to it. For example, for Lab A "gene profiling" requires using technology at a nearby medical school. The investigative practice of *in vitro* simulation is deeply implicated in these mappings. To address the "barrier" of "mechanical properties" of endothelial cells *in vivo*, for instance, requires designing and using flow chambers and collagen gel constructs.

Given the hybrid nature of the *in vitro* models, a major learning challenge for these researchers is to develop selective, integrated understandings of biological concepts, methods, and materials and engineering concepts, methods, and materials. By "selective," we mean that a researcher-learner needs to integrate, in thinking and experimenting, only those dimensions of biology and engineering relevant to his or her research goals and problems. For example, in Lab A, researchers need to develop an integrated understanding of the endothelial cell in terms of the stresses of fluid dynamics of blood flow in an artery. Further, in designing and conducting experiments with devices, researchers need to understand what engineering constraints they possess deriving from their design and construction, and what limitations these impose on the simulation and subsequent interpretation and inferences. That is, the device needs to be understood both as device *qua* model of *in vivo* phenomena and device *qua* engineered model.

Building activities centered on the *in vitro* models are pervasive in the lab and serve several functions. The artifact models connect the cognitive practice of *in vitro* simulation with social practices; for instance, much initial mentoring and learning of laboratory ethos takes place in the context of cell culturing – something all newcomers must master. The processes of building hybrid physical models also provide opportunities for the researcher to build integrated mental representations (Nersessian, 2009). For instance, building a physical construct to condition with the flow loop facilitates building a mental representation that selectively integrates concepts from cell biology and fluid dynamics – one that represents, for example, biological aspects of the endothelial cells with respect to mechanical forces in terms of the integrated concept of arterial shear rate (force of blood as it flows over these cells, causing elongation, proliferation, and so forth).

In experimental situations models tend to be put into interlocking configurations, that is, models stand in particular relations to other models. A brief look at the design and execution of a significant Lab A experiment will provide a means of articulating this dimension of bioengineering integration. Soon after one graduate student (designated A7 in Figure 35.1) arrived (with a background in chemical engineering) she was designated the "*person who would take the construct in vivo*," meaning that her research was directed toward conducting experiments with an animal that serves as a model for the human body in the context of the experiment. This objective immediately required that she would (1) need to design and build a construct that would both more closely mimic the functional characteristics of an in vivo artery than was used in most other experiments and would have sufficient strength to withstand the force of in vivo blood flow; (2) modify the flow loop so that it would work with constructs in

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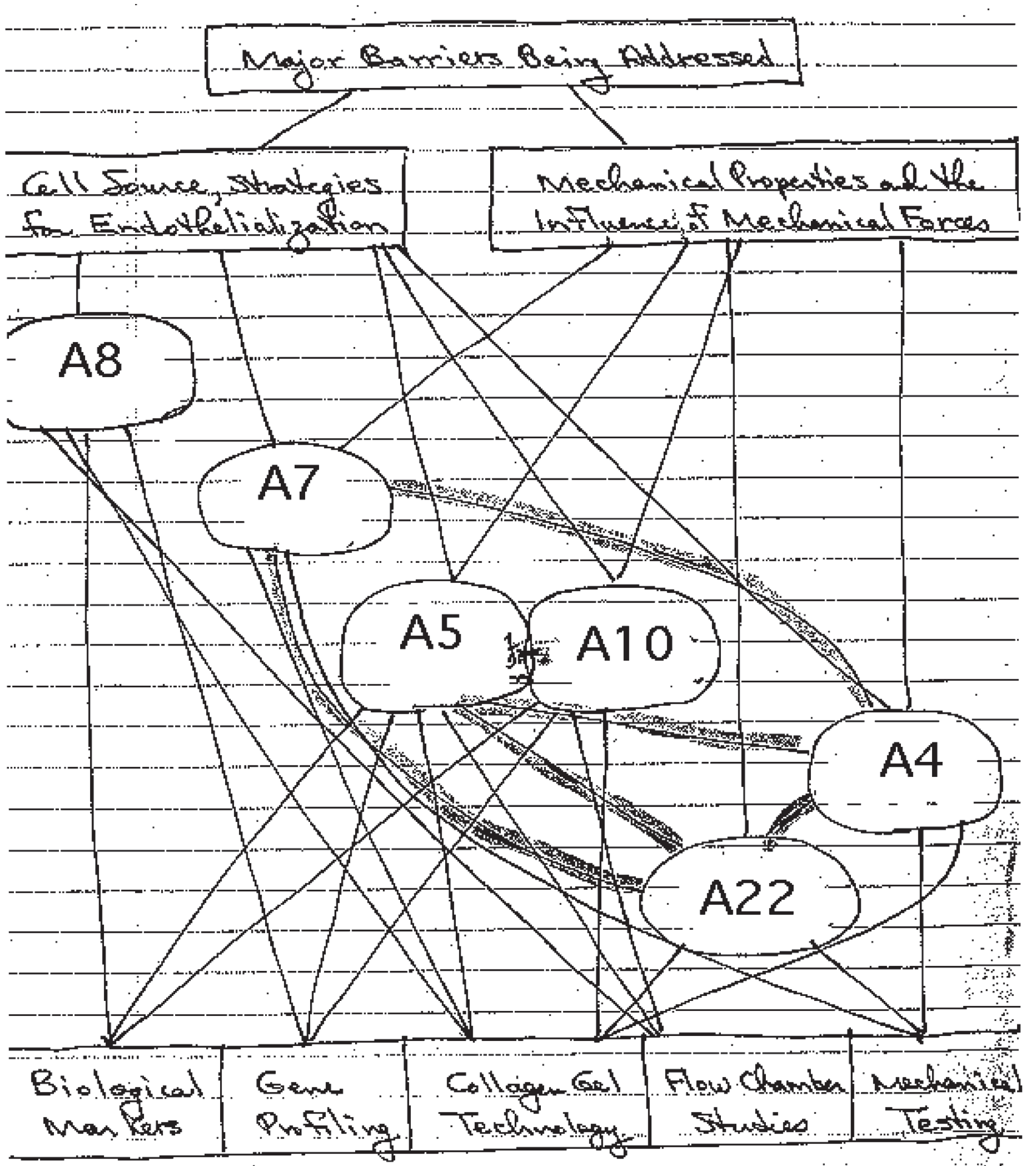

Figure 35.1. The adaptive problem space of the tissue engineering lab at a specific period in time as drawn by the lab director.

tubular form, and (3) arrange for an animal (baboon) to be surgically altered so as to experiment with the construct outside of its body and in a minimally invasive way. It also required that she bring together the strands of research being conducted by nearly all the other lab members, as represented by the lab director in Figure 35.1. As she expressed it, "to go to an in vivo model we have to have all, well most of the aspects that people have studied."

When we started, she had been in the laboratory about a year, but was still in the process of defining the specific goals and problems of her research. Her final overarching formulation of the problem was to determine whether it would be possible to use circulating endothelial cells ("progenitor cells") derived from a patient's peripheral blood to line the vascular graft. The endothelial cells that line the artery are among the most immune sensitive cells in the body. If the

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patient's own endothelial progenitor cells could be harvested and used that would greatly enhance the potential of a vascular graft. However, the progenitor cells do not modulate thrombosis, which is a function of the mature cells. She hypothesized that shear stress conditioning (by means of the flow loop) the construct before implantation would solve the problem of platelet formation and the resulting thrombosis.

It is instructive to examine her own succinct summary statement as an example of dimensions of hybridization.

> *We used the* ***shunt to evaluate platelet deposition*** *and that would be – in other words – were* ***the cells, as a function of the treatment*** *that they were given before they were seeded onto* ***the engineered tissue****, able to prevent blood clotting? And so we specifically measured the number of platelets that would sit down on the surface. More platelets equals a clot. So, it ended up being that we were able to look at* ***the effects of shear stress preconditioning on the cells ability to prevent platelets*** *and found that it was actually necessary to* ***shear precondition*** *these blood derived cells at* ***an arterial shear rate****, which I used 15 dynes per square centimeter compared to a low shear rate, which in my case I used like 1 dyne per square centimeter, so, a pretty big difference. But I found that* ***the arterial shear*** *was necessary* ***to enhance their expression of anti-coagulant proteins*** *and therefore prevent clotting. So in other words,* ***the shear that they were exposed to before going into the shunt*** *was critical in terms of magnitude, for sure.*

The bold terms mark reference both to hybrid interdisciplinary models as they function in her understanding and reasoning and to the various hybrid physical models. To unpack a few of her expressions "the cells" are the endothelial progenitor cells she extracted from baboon blood and seeded onto the "engineered tissue" (vascular construct model). The "treatment" they received was "shear stress preconditioning" conducted by using the modified flow loop model. The objective of her research was to determine if, and at what level, the preconditioning ("arterial shear" simulation) of constructs would "enhance their [cells] expression of anti-coagulant proteins" ("prevent platelets"). She found, through several iterations of the entire model-system ("used the shunt [animal model] to evaluate platelet deposition"), that the in vivo human arterial shear rate ("15 dynes/cm^2") was required for sufficient protein expression ("was critical in terms of magnitude"). Likewise, her designing and experimenting by means of the hybrid baboon model-system led to a revision of her conceptual understanding of the vascular construct so as to reflect the necessity of using arterial shear in order to prevent thrombosis. From this articulate summary of research project and findings, we can detect that this researcher has developed into both an integrative biomedical engineer and a potential boundary agent with interactional expertise for the relevant disciplinary communities, such as medicine.

Transdiscipline: Integrative Systems Biology Research Labs

This exemplar draws from our ongoing investigation of an emerging transdiscipline, integrative systems biology (ISB), which focuses on two labs that self-identify as conducting research in ISB; one that does only computational modeling and the other that does both modeling and experimentation. They are both largely populated by student researchers with engineering backgrounds. The modeling lab has various bioscience external collaborators. The overarching problem of the labs – and the field of ISB in general – is: How to develop a non-reductionist understanding of how multilevel biological systems function? As the modeling lab director stated, "[systems modeling] allows us to merge diverse data and contextual pieces of information into quantitative conceptual structures; analyze these structures with the rigor of mathematics; yield novel insight into biological systems; suggest new means of manipulation and optimization." Our findings are preliminary in this exemplar since we have only been conducting this research for two years.

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What is striking is that the various possible configurations for research in this adaptive space are numerous and continue to emerge, and our cases provide only a subset. Still, we have gained some important insights into transdisciplinary engineering research in ISB.

Although there are many different kinds of researchers in this space at present, the aspiration of this field, still in its infancy, might be characterized as addressing the research problems that lie at the intersections of computing/applied mathematics, biosciences, and engineering to create an emergent transdisciplinary space that allows for multiple kinds of adaptations and boundary agents. The goal is integration of novel high throughput technologies, modeling, and experimentation to address biological problems, but the way the field looks at present, researchers in ISB will largely remain in disciplinary fields while working in collaboration with other disciplinary partners. But unlike the multidiscipline, in this case each field in the adaptive ISB problem space will likely penetrate and change significant practices in regions of the collaborating fields. For instance, for the aspirations of the field to succeed, modeling needs will lead to changes in biological practices, for example, with respect to the kinds of data collected; high-throughput technologies that generate reams of data have and will continue to change the practices of both bioscientists and modelers.

Initially, we, along with much that is written about this emerging field, cast the participants as computer scientists/applied mathematicians, biologists, and engineers. So, it was quite interesting to note early on that they tend to identify themselves and other members of the community functionally as "modelers" (those who apply mathematics and develop computational models/simulations) and "experimentalists" (those who conduct bench top experimentation) which we see as already a move into a *transdisciplinary* adaptive space. In our study nearly all the researchers have engineering backgrounds, though ~~most~~ identify themselves as having had a "*generalist*" education. As one participant from Europe stated of her electrical engineering degree: "they learned us to learn, not to learn something." As discussed in the Conclusion section such a generalist background might be important for developing the cognitive flexibility required to become integrative researchers in this field.

Lab G comprises only modelers and is led by a senior pioneer in biological systems modeling. The overarching problem of the lab is to develop rigorous computational models of biological phenomena at the systems level. Most have never done this kind of modeling before entering the lab. The biological problems researchers work on are provided by experimentalists external to the lab. Experimentalists usually contact the lab director asking him to model some data they consider have potential to benefit from such analysis in areas as varied as biofuels, Parkinson's disease, atherosclerosis, and heat shock in yeast. The fact that they largely depend on bioscience problems that are generated external to the lab has the implication that researchers (who are engineers) have to develop the facility to go deeply into the experimental literature that changes with each modeling project with little course work or bench top experience in biology. The lab does formulate its own research problems in methods development, such as new methods of parameter estimation.

Lab C comprises both researchers who do only modeling and those who do both modeling and experimentation. The director is a young assistant professor who is fully conversant in both modeling and experimental methods. The overarching problem of the lab is to understand cell signaling dynamics in a reduction–oxidation (redox) environment in immunological contexts; in effect, to integrate redox cell biology and biochemistry research through systems modeling. The specific biological problems, thus far have been chosen by the lab, include immunosenescence and drug resistance in acute lymphoblastic anemia. Their methodological research has largely been in the experimental area, such as the design and development of microfluidic devices to

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generate high-throughput data for their models. Experimentation in Lab C is directed toward getting parameters needed to develop and validate models that they develop initially from the same kind of literature searching as lab G. Experimentation is conducted either by the student who is building the model, who is developing into a hybrid researcher, or, for the pure modelers, by the lab director or the lab technician, who has an MS in molecular biology.

Unlike BME, which has a relatively unified vision of how research and training should proceed, ISB is experiencing what the Lab G director calls a "philosophical divide." First, with respect to lab structure, Lab G is an instance of what we call a *unimodal lab*. Such a lab can comprise all modelers or all experimentalists, such that the transdisciplinarity manifests as two separate research partners undertaking complimentary but different activities. The philosophy that underlies this research modality is that a lab does the best research if its members are deeply engaged in only one kind of activity. A potential disadvantage of this modality is that each research partner is dependent on the sustained interest and engagement of the other for successful biosystems modeling, despite there being little interaction between them. From the modeler's perspective, there is often a significant phase lag between model building and generation of the needed experimental data, as the Lab director put it, "you need 10 experimentalists for every modeler" and everyone needs "ongoing technical problems to work on so that time is not wasted [waiting for experimental data]." As for advantages of unimodality, our research provides insight into only the modeler's perspective. One advantage is that the development of operating principles and novel theoretical approaches are driven by researchers developing perspectives across different domains and also by the poverty of data.

Lab C is what we characterize as a bimodal lab were bimodality can manifest as either a within-lab collaboration between an experimentalist (or hybrid researcher) and a modeler or by a hybrid researcher who carries out his or her own modeling and experimentation. This approach has the advantage of the lab being able to focus deeply on biological problems of its own choosing and of being able to design its own experiments and collect data as needed in a more timely manner. A potential disadvantage is that the within lab collaborations could prove not to be able to meet the needs of someone who does only modeling (unless the lab has a large number of people engaged in experimentation); another is that it is an open question as to whether the hybrid researchers will be able to develop the requisite level of expertise in both modeling and experimentation. This latter question points to another philosophical divide in the field: how best to train those wishing to become hybrid researchers.

The main divide in training hybrid bimodal researchers is over whether such training should be sequential or parallel. All three possible configurations of training are represented in the labs we have studied. A postdoctoral researcher, who collaborates with Lab G was first trained as an experimentalist and then migrated to learning and doing only modeling. The Lab C director first did only modeling and then nearly five years into her Ph.D. started on experimental work. She believes her student researchers who want to become hybrids need to be trained simultaneously in both. As she said, "I tell my students never to do this [sequential]. You should always do these things in parallel. I ran into the learning curve early graduate students face – only here I was 4.5 years in and starting from scratch on some of these things." The Lab G director believes that students should only be trained in one or the other, because otherwise there is "the problem of diluting both sides" with "modeling lite and experimenting lite." If a person wants to become bimodal, then he or she should train sequentially through a post-doc in the other area.

Although the jury will be out on this divide for some time, it is interesting to compare the perspectives of the two who have

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recently completed their training. The postdoc in Lab G when asked how he would run his own lab and student training stated, "I lose a lot of time going from one side to the other . . . its more efficient to have a student doing lab work and another dealing with the problems of modeling . . . They should be in the same lab, they need to see each other working." On the other hand, the Lab C student who recently graduated with a dissertation project that combined both said she was concerned about having someone else do her experimental work because they might not "really understand the modeling project.. can't accurately come up with a good enough experimental protocol to get what it is I need." Of her own experience, she said "I like the idea that as I'm building my model things are popping up in my head on wow this would be a good experiment. I plan out the experiment and then do it. I like the idea I'm being trained to do both so I have enough tools in my toolbox."

General Discussion

In the Rad Lab case we see multidisciplinary interaction within a trading zone where Schwinger was a central boundary agent. The equivalent circuits are the boundary objects. There was integration of concepts and methods specific to the wave guide calculations. We would argue in some cases trading zones can also be adaptive spaces. For instance, in this example one emergent phenomenon was a new way of thinking for Schwinger which he used in a highly productive manner to resolve problems in his discipline. On the engineering side, a new field of microwave engineering emerged. The interaction was driven by problems stemming from a specific situation, World War II, and collaboration was not driven by internal problems originating in the disciplinary fields. Multidisciplinary interactions are often serendipitous, related to a specific problem, and transient. Once the problem has a satisfactory solution (or proves insoluble) the collaboration ends and the practices of the participating disciplines are largely unaltered, even when a new field might have been spun off.

In the BME lab cases there is emergent hybridization in an adaptive space initiated by pioneering engineers who participated in collaborations and thus acted as boundary agents in the early days of the field. To create the emergent hybrid systems of thought, methods and materials they believed would move the field forward required a different model of research than that of two researchers from different disciplines collaborating. BME's answer has been to design a different kind of researcher – individuals, who might be considered themselves as "hybrid systems." The integrative biomedical engineer is both a self-sufficient ID researcher and prepared to be a boundary agent able to collaborate with researchers in other disciplines. Over time this ID field is transforming into an interdiscipline that integrates elements of all three original disciplines, and creates individuals who identify as hybrid biomedical engineers.

In the ISB lab cases there is interpenetration of disciplines that are mutually effecting changes as well as various kinds of emergent adaptations at their intersections. This is a newly configuring adaptive space and how its research practices and researchers will evolve is quite open at present. Although there are fully hybrid individuals emerging in this space, the current aims of the participants seem likely to make this exception, rather than the rule. The implication of this is that developing interactional expertise is crucial to functioning as boundary agents in this adaptive space. From our research thus far, it appears that the requisite interactional expertise is not sufficiently developed for what one researcher called "synergistic" collaboration in at least three ways. First, model building begins with the development of a pathway for the biological phenomenon under investigation. The pathway performs as a boundary object in that it is a meaningful representation for both experimentalists and modelers. At present it is the primary means of communication of research results and ideas between collaborators. However,

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our investigation indicates that the model needs to become a boundary object because it is the vehicle of integration and the engine that is pushing systems understanding forward. Experimentalists need to understand how the data will be used in order to conduct experiments that will provide sufficiently informative data. Second, modelers need to develop experimental understanding at the bench top level in order to know enough about experimental design and execution to have a realistic sense of such things as what is experimentally feasible, the reliability of the data, and the costly and time consuming nature of experimentation. Finally, all participants need a basic systems understanding as provided by engineering fields.

Conclusion: Implications for Learning

Given the varieties of interdisciplinarity illustrated in these case studies, how can we best prepare engineering students to participate in these interdisciplinary configurations? Are there certain pedagogical configurations that best support the development of interactional expertise making it possible for teams to find common ground, to identify and leverage boundary objects and to more smoothly exchange information and intent toward reaching a commonly valued goal? And where do we situate these learning experiences in the overall curriculum?

We contend that while each variety of interdisciplinarity implies a particularized pedagogic approach, in all cases, students need to develop what has been called *cognitive flexibility* (Spiro, Feltovich, Jacobson, & Coulson, 1992) or the ability and knowledge to engage a problem domain, an object or a representation from more than one perspective. We see this as the ability to adapt in interdisciplinary problem spaces, becoming boundary agents in problem situations that require them, while also leveraging boundary objects with their intersecting social worlds/meanings. Developing this ability requires students to work in complex, ill-structured knowledge domains not simple, well-structured ones. Problem-driven learning experiences are particularly appropriate in developing cognitive flexibility because such experiences situate students in real-world, complex situations that require teams to work together to achieve a goal and possibly to pursue and evaluate multiple routes and solutions. To date there has not been much research conducted on designing learning environments targeted specifically toward creating interdisciplinary engineers (Richter & Paretti, 2009). Here, we offer an example from our own institution of three different learning environments where students can practice a specific form of interdisciplinarity.

Bio-inspired Design: A Multidisciplinary Experience

In recent years, engineers have started to look to biology as a source and inspiration for design solutions, on the assumption that evolutionary adaptation has produced simple but elegant solutions to complex problems in the natural world. However, translating between the descriptive world of biology and the quantitative systems world of the engineer is challenging. Like the trading zone on an African river, these "tribes' do not share a common language even though they may share common concepts. Developing the kind of interactional expertise that makes it possible to span the boundaries of these disciplines is of paramount importance. Working with this concept, the bio-inspired design course seeks to develop individuals who are able to translate biological solutions into engineered designs. To do this, students from biology, engineering and industrial design work on two team projects over the term towards developing the interdependent skills of interactional expertise and analogical reasoning (Vattam & Goel, 2011; Vattam, Helms, & Goel, 2010) that will enable them to find commonalities across the disciplines. Analogical reasoning entails looking beyond surface features or application of a given object in one domain for a deeper structure than can be mapped or translated into another domain or application.

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Such reasoning facilitates exchange across disciplinary borders.

Leveraging the idea of a boundary object, teams first are invited to identify a biological solution in the natural world and then to translate that into a solution in the engineering world (solution-driven design). In this first case, the design in nature can be viewed from the biological perspective (evolutionary adaptation) but also the engineering perspective (function and form). The second project works in the opposite direction where an engineering problem is identified and the team seeks a biological solution that can be applied. The multidisciplinary teams work together on both projects learning to translate from one perspective/world to the others while practicing looking at the same object from another perspective. Whereas, the first project brings the engineer and design student deeply into the world of biology, the second brings the biologist into the world of the engineer and designer. Learning to parse a problem solution from biological, engineering, and industrial design perspectives promotes the kind of cognitive flexibility indicative of boundary agents and those able to barter in trading zones. This educational model for promoting a multidisciplinary practice can also be found in a number of capstone design experiences (Adams, Beltz, Mann, & Wilson, 2010; Adams, Mann, Forin, & Jordan, 2009; Adams, Mann, Jordan, & Daly, 2009; McNair,Newswandera, & Borrego, 2011) as well as community-based service projects.

Problems in Biomedical Engineering: An Interdiscipline Experience

Biomedical engineers need to be true integrative, hybrid thinkers and problem-solvers if they are to utilize engineering analysis and methods to design healthcare solutions. The *model-based reasoning* exemplified in the development of in vitro device discussed in the preceding text depends on the ability to simultaneously view an object or application or representation from multiple dimensions and perspectives (Nersessian, 2002, 2008; Nersessian & Patton, 2009). This integrative ability needs to be practiced repeatedly over time and in a variety of circumstances. Because learners need multiple opportunities to practice this integration, developing a biomedical engineer is not about a single course, but a total curriculum systematically designed to foster flexible, responsive model-based problem solving. The *Problems in Biomedical Engineering* course was developed using a translational approach whereby the design principles for the course were derived from our ethnographic investigations of learning in bioengineering research laboratories (Newstetter, 2006; Newstetter et al., 2010). The goal was to create an adaptive space by replicating some of the kinds of (authentic) activities undergraduates and graduate students undertake in the research labs to the extent possible in a (synthetic) classroom.

Learning in this class is driven by the need to solve three complex, interdisciplinary problems over the term. The problem sequence is set but each problem can be changed sufficiently on the surface so that every term is different. The problems all require teams of eight students to integrate knowledge and skills from biosciences and engineering in arriving at a problem solution related to a medical context. As an example, the first problem focuses on the challenges of screening for disease. The team needs to evaluate current screening technologies for a given cancer and then make recommendations for future screening protocols based on research using peer-reviewed science and medical and engineering articles. Overall, the problem requires the integration of cancer biology, probability statistics, and screening technologies across the molecular to the whole body scale. Often cost–benefit analyses and social issues become part of the problem solution. To support this integration and complex problem solving, teams work in specially designed 10 × 10 classrooms with writable walls which they use to represent, explain, and speculate individually and as a group. They also benefit from interacting with a faculty or post doc facilitator who makes his/her reasoning and problem solving strategies more "visible"

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through asking probing questions just as a lab director would do with lab members. The goal of this course is for students to start the process of learning to integrate skills, knowledge, methods, and representations from the sciences and engineering toward solving real-world problems, practices that define what it means to be interdisciplinary.

Three Possible Models: A Transdisciplinary Experience

Preparing students for transdisciplinary practice implies a very different educational scenario from the two above. First, our studies suggest that graduate school is where this needs to happen. We have found that the researchers who inhabit this world and who claim identities as either modelers or experimenters have sophisticated skills and knowledge already, which they bring to bear on the lab problems. This deep disciplinary training gives them what they need to begin their graduate work. At the same time, they commonly have blind spots to the needs, values, or constraints of the other camp. Modelers need a certain kind of data, which the experimenters may not value and so they will not take the time to perform the experiments. At the same time, the experimentalist may see the modeler as just reproducing her study *in silico*, which is not particularly interesting or relevant. These misalignments can lead to a certain stereotyping one of the other, which is counterproductive. We offer three different models for creating adaptive spaces to bring greater alignment and understanding to the modeler/experimenter configuration.

A first remedy followed by Lab G was a temporary summer excursion into the other camp. Two graduate student modelers from engineering backgrounds spent two months learning experimental procedure, conducting their own experiments and collecting data. In doing so, they have begun to develop an appreciation for the challenge of gathering data both from the time and expense perspective. They also developed the ability to read papers with enhanced understanding of techniques, equipment, and procedures used in lab work. Another benefit was the confidence the modelers developed in talking directly with the experimenters (interactional expertise) from spending some intense time at the bench top. On the flip side, if experimentalists were to spend time with modelers, they could better see the possibilities of modeling for prediction, speculation, and experimentation. They could also better understand why the modeler needs certain kinds of data. Further, the experimentalist could become a better consumer of modeling papers for his or her own work.

A second model would be the design of a collaborative laboratory-based graduate course that paired modelers with experimenters. The task would be to address a problem that could benefit from both approaches working in tandem. The need for interactional expertise would be obvious as the team traversed and engaged the same task from two different methodological and epistemological perspectives.

A final model would be an integrative modeling course where experimenters and modelers were again paired to address a problem area, for example, a disease like cystic fibrosis. The experimenter could be very helpful in finding resources for the model and translating them for the modeler. Likewise, the modeler would need to articulate her needs in a way that would allow the experimenter to be a resource. These educational models do not advocate for developing fully hybrid (bimodal) researchers, but rather for individual adaptation of the kind that creates symbiosis or mutualism, where both come to appreciate and see the value of the practices of the other. Such educational experiences can promote the kind of cognitive flexibility and interactional expertise for the transdisciplinary space where values, practices, and epistemologies differ.

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Footnote

1. An exception on practice is the chapter on civil engineering by Culligan and Pena-Mara in the recent *Oxford handbook of interdisciplinarity* (Frodeman, Klein, & Mitcham, 2010, pp. 161–174), which provides a valuable resource for developing a broad understanding of the current "terrain" of ID research. Notable exceptions on education are a survey of the current landscape with respect to undergraduate education (Lattuca, Trautvetter, Codd, Knight, & Cortes, 2011) and research on undergraduate design teams (see, e.g., Adams, Beltz, Mann, & Wilson, 2010; Adams, Mann, Forin, & Jordan, 2009; Adams, Mann, Jordan, & Daly, 2009; McNair, Newswandera, Chad, & Borrego, 2011).

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