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Title: Interdisciplinary Work at the Frontier: An empirical examination of expert interdisciplinary epistemologies

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Interdisciplinary Work at the Frontier:

An empirical examination of expert interdisciplinary epistemologies

Abstract

At the frontier of knowledge production, boundary-crossing takes place at a variety of disciplinary crossroads. This paper reports the results of an empirical study of work carried out at five major research institutions. The study is based of in depth interview data (N = 55), complemented by samples of published work and institutional documentation. At least three approaches to interdisciplinary inquiry are identified: *conceptual-bridging, comprehensive,* and *pragmatic*. Each approach embodies preferred epistemological mechanisms for disciplinary integration and favors particular validation criteria by which interdisciplinary insights are assessed.

> "The most exciting science in the 21st century is likely to evolve among not within traditional disciplines… yet the education of scientists has historically been constrained by disciplines, paralleling patterns of science funding." (Sung et al, 2003)

Introduction

Interdisciplinary research has emerged as a hallmark of contemporary knowledge societies. In some quarters, theoretical physicists mathematically model phenomena traditionally beyond their purview: life, death, and human interactions (Wolfram 2002, Crutchfield 2002). In other quarters, artists borrow computer-code to redefine aesthetic expression. Indeed, the most pressing challenges of cultural and environmental survival today are being addressed at the fertile intersection of multiple disciplines (e.g., mitigating climate change, developing biomedical technologies, legislating migration).

A growing number of interdisciplinary initiatives in the US and Europe have shed light on the need for (and difficulties of) cross disciplinary dialogue. In research, new funding opportunities and intellectual gatherings have nurtured exchange, but they have also encountered the problem of defining quality in interdisciplinary work (Feller 2002). In higher education a growing number of teaching programs termed "interdisciplinary" have been met with uncertainty in the absence of empirical foundations to delineate adequate pedagogies and aims (Rhoten et al 2006). At the center of the problem lies the challenge of defining what is meant by "interdisciplinary research," how it is best conducted, and how to judge its quality.

Concerned with the chasm between the demand to prepare our youth to address complex matters of cultural and environmental survival on the one hand, and the lack of empirically based guidelines for interdisciplinary instruction on the other, my colleagues and I at the Interdisciplinary Studies Project at the Harvard Graduate School of Education turned our eyes to the work of experts at the frontier of knowledge production in established interdisciplinary research institutions. We asked, what does interdisciplinary work look like when conducted by experienced individuals? A systematic understanding of the core mechanisms by which experts merge disciplinary traditions in a meaningful way can inform educators seeking to help students move beyond over specialization or ill-grounded interdisciplinary initiatives.

In this paper, I report the results of a qualitative study of interdisciplinary research as described by experts working at a variety of disciplinary intersections. Two questions are addressed through analysis of interview data and samples of expert work (N=55):

1. How do researchers integrate disciplinary perspectives to advance their work?
2. What criteria do they use to validate their research outcomes?

My analysis reveals that amidst the broad variety of seemingly idiosyncratic interdisciplinary research practices, at least three approaches to interdisciplinary inquiry can be identified: I term them *conceptual-bridging, comprehensive,* and *pragmatic.*. Each approach embodies its own preferred epistemological mechanisms for disciplinary integration and favors validation criteria by which interdisciplinary insights are assessed, accepted or rejected.[i] A *conceptual-bridging* approach examines single concepts, principles, or laws (e.g., network behavior) that can account for phenomena studied within a broad variety of disciplines. Disciplinary integration builds on careful analogical analysis and is modeled after formal disciplines such as mathematics, informatics, logic, analytical philosophy and theoretical physics. A *comprehensive* approach to interdisciplinary research produces multi-causal explanations of a phenomenon whose interrelated components are typically studied by different disciplines (e.g., biological and cultural human variation). In this case disciplinary perspectives are interwoven to account for the phenomenon in its full complexity. This approach is modeled after synoptic disciplines like history, geography, anthropology, or naturalistic biology. Finally, *pragmatic interdisciplinarity* offers viable solutions to problems in the social, political, medical, and technological realms, among others. In this outcome-centered approach, integration involves envisioning an effective and workable final product and back-filling through strategic selection of disciplinary inputs. This approach is modeled after professional work –e.g., engineering, journalism, architecture, and graphic design--and upholds standards of effectiveness and viability. In what follows, I describe previous attempts at capturing the epistemological nature of interdisciplinarity, propose a definition of interdisciplinary work, and introduce the empirical study upon which I ground my characterizations. I then examine the three approaches to interdisciplinary integration in detail, grounding each definition in particular examples of interdisciplinary work. In the conclusion, I revisit the proposed typology and outline some possible lines of inquiry for future investigation.

Background: Toward a definition of interdisciplinary research

Despite its pervasiveness in academic and R&D centers, the concept of interdisciplinarity remains elusive and its systematic empirical study scarce. The term is adopted to refer to a broad array of endeavors—from the work of a biochemist studying gene regulation in a company, to the efforts of a high school teacher to introduce visual arts in a science class, to a sociologist's writing of music about Black heritage. This semantic evasiveness is exacerbated by the fact that current scholarly debates about interdisciplinarity involve social, political, and cognitive dimensions. Moreover, with few exceptions (Feller 2002, Guetzcow et al 2003, Lattucca 2001, Laudel 2001, Rhoten 2003) empirical examinations of interdisciplinary work take the form of individual case studies, limiting the comparability of results across cases and disciplinary combinations.

Illuminating insights into the nature and challenges of interdisciplinary research stem from highly conceptual approaches to interdisciplinary work (Klein 1996, 1994, Kockelmans 1979, Newell 1998), and from content-specific explorations (Caplan et al 2000 2001, Diamond 1997 2005, Dawkins 1976, Galison 2001 2003, Gould 2003, Wilson 1998). For example, in a classic analysis of “boundary crossing,” Klein challenges the popular claim that so-called “soft” disciplines have more permeable boundaries than their “hard” counterparts (Klein, 1994). Instead, she proposes that there are two kinds of disciplines “that are associated with such a high permeability that they are often described as inherently interdisciplinary… the *applied* and the *synoptic* [disciplines].” Klein characterizes applied disciplines (e.g., law, engineering, architecture) as problem-driven and more eclectic than purist in their approach to problems perceived “as pragmatic more than theoretical” (Klein, 1996, p. 39-40). This type of work is informed by the “eclecticism of practice” (Schwab, 1978). Synoptic disciplines, on the other hand (i.e., history, geography, anthropology and philosophy), exhibit a looser aggregation of interests that yield natural interdisciplinary ventures.

While theorists of interdisciplinarity like Klein, Kockelmans and Newell offer general accounts of integration, scholars whose reflection about interdisciplinarity stems from deep involvement in particular domains (e.g. biological evolution), inform conceptualizations with vivid detail. In their attempts to articulate forms of knowledge production that bridge C. P. Snow’s canonical “Two Cultures,” Wilson and Gould proposed contrasting views of interdisciplinarity that echo, like Klein’s, some of the distinctions we encountered in the field (Snow, 1993). Wilson confers to science a privileged place as a unifying ground for all forms of knowledge by virtue of yielding findings that are highly reliable, law-like, and rigorously measured. “Complexity is what interests scientists… and reductionism [viewed as science’s unique leverage] is a way to understand it” (Wilson, 1998, p. 54). In Wilson’s view, interdisciplinary coordination involves reducing problems of study in the social and cultural world (e.g., social behavior, art, and technology) to their basic bio-chemical components (e.g., the neurological categories that might explain the social or creative experience). Gould, on the other hand, critiques Wilson’s proposed reductionism and argues that the best interdisciplinary work recognizes the intrinsic differences in disciplinary forms of knowledge, each embracing a unique [and often complementary] form of explanation (Gould, 2003, p.255). Independent of whether one agrees with one or another position, their accounts speak to the very problem examined in this paper: how disciplinary insights can be brought together and their integration assessed.

In sum, the literatures on interdisciplinarity vary vis-à-vis their definition of "interdisciplinary research" (i.e., referring to a broad range of integrative practices); the dimensions of interdisciplinary research deemed essential (i.e., social, conceptual, political); and the epistemic foundations on which insights about interdisciplinarity are based (i.e., anecdotal, theoretical, empirical). Against this background, in this study, I define interdisciplinary inquiry as the pursuit of an advancement in understanding—i.e. an enhancement in our capacity to solve problems, produce explanations, create products, and raise questions--by means of bringing together bodies of knowledge and modes of thinking stemming from two or more disciplines. Three features are central to this definition. First, interdisciplinarity is *purposeful*; it is a means to advance our understanding, not an end in itself. Second, it is *disciplined,* incorporating not only disciplinary findings but also the modes of thinking characteristic of the disciplines involved. Third, it is *integrative*; it seeks to intertwine (not juxtapose) disciplinary perspectives in ways that *leverage* understanding with a clear sense of added value that is unlikely to emerge through single disciplinary approaches.

Methods

Informants

Fifty five individuals working in five recognized interdisciplinary research institutes were interviewed for this study. The Santa Fe Institute (SFI) in New Mexico, is a basic research center founded in 1984 to study common themes that arise in natural, artificial, and social systems through lenses such as chaos and complexity theory. The MIT Media Lab (ML), in Cambridge Massachusetts, was founded in 1980 to study the future on human computer interaction. The Research in Experimental Design group at XEROX-PARC (RED) in Palo Alto, California, was the research division of Xerox Corporation and worked with individuals whose skills ranged from architecture and cultural theory to programming and video production in the design and exhibition of future technologies[1]. The Center for the Integration of Medicine and Innovative Technologies (CIMIT) Cambridge, MA, is a multi-institutional organization that facilitates collaborations among physicians, scientists and engineers to develop minimally invasive medical technologies. The Center for Bioethics at the University of Pennsylvania (CB-UP) brings together experts in philosophy, social sciences, law, and life sciences to conduct empirical research in bioethics and inform practice in the life sciences and medicine. Five additional interviews were included in the data set due to the informative descriptions of research provided. These interviewees were associated with the Human Biology interdisciplinary major at Stanford University [HUMBIO] where biological and social disciplines are brought together to examine matters of human development (e.g., incest taboo, sexuality, and disease).

Research centers were selected on four grounds: (a) They reflected a long standing commitment and accumulated experience (five years or more) in quality interdisciplinary research; (b) leadership and researchers showed willingness to reflect about the nature of interdisciplinary research and its challenges; (c) collectively, the centers represented a broad range of disciplinary emphases and combinations (e.g., history and mathematics, physics and biology, music and computer science); and (d) researchers were dedicated to exploring novel disciplinary combinations as opposed to more institutionalized paths ones (e.g., art history, biochemistry, and sociology of science). We emphasized such novel disciplinary combinations because we expected

[1] RED closed operations in 2003.

that creating uncharted disciplinary integrations would require that researchers become epistemologically aware of distinctions and connections among disciplines, and reflective about the challenges in interdisciplinary work. We deemed our informants' readiness to discuss these epistemic dimensions of their work key for the success of our research. The four criteria (years of experience, reflective stance, diversity and novelty of disciplinary combinations) were then used by senior administrators to propose particular researchers as informants for our study (Table 1: Informants by center and main disciplinary affiliation).

Data Collection

The data corpus for this paper consisted of 55 in-depth, semi-structured interviews, selected samples of researchers' work (publications, exhibits, reviews), and institutional documents (homepages and external publications describing the centers). Each interview of an average length of 1.5 hours was conducted at the research centers by two interviewers. To prepare for the interviews, we familiarized ourselves with each center's institutional mission and procedures as well as with our informants' biographies and published work.

The interview protocol covered organizational, social, and intellectual dimensions of interdisciplinary work. A considerable portion of the protocol was dedicated to disciplinary integration and quality assessment, a central area of concern in our study. Researchers were asked to describe their current interdisciplinary work in detail, explain how they integrated perspectives and discuss the indicators of qualities in their own (and others') work. Probes sought to elicit perceived challenges of assessment and integration. Interviews were fully transcribed. Eighty percent of the full transcripts, and one hundred percent of the selected quotes included below were reviewed for accuracy by interviewees. All informants signed a consent form before being interviewed.

Analytic Strategy

Two researchers (a researcher in the team and myself) coded all transcripts for references to: (1) stated purposes of interdisciplinary work; (2) stated mechanisms of integration; and (3) the researchers' approach to quality assessment. Initial content analysis yielded twelve categories referring to forms of integration (e.g., checks and balances, complex causality, embodying, contextualizing, disciplinary expansion, aesthetic synthesis). Particular attention was given to stated challenges of disciplinary integration. Upon further coding, some categories (e.g., contextualizing, complex causality) were regrouped yielding the distinct approaches to integration here proposed. Other categories (aesthetic synthesis) were excluded from further analysis because they emerged in isolated cases. A subset of eight transcripts rich in descriptions of integrative processes were selected for in-depth study and further triangulation with samples of published work.

Results

Researchers in our sample employed three primary approaches to interdisciplinary research: *conceptual-bridging*, *comprehensive*, and *pragmatic* were identified. Each approach embodies a distinct mechanism for disciplinary integration and favors unique standards for assessment fit to the problem under study. In what follows I introduce each approach beginning, in each case, with a close examination of one individual's work.

I. A *conceptual-bridging* approach to interdisciplinary research

> We are now looking at many kinds of networks. When one says "networks," biologists think "metabolic networks," or if you're an electrical engineer you think "power grids," or if you're a neurobiologist you think "neural networks." Many basic, common questions cut across different disciplines--questions that bear on how to quantify how the topology of a network controls or facilitates the behavior on the network. (James Crutchfield)

Overview

James Crutchfield, a leading theoretical physicist at the Santa Fe Institute, eloquently illustrates a conceptual-bridging approach research. Disciplines are brought together under a unifying concept, principle or mechanism thought to account for a variety of phenomena. Such approach involves the identification of a *bridging motif* (e.g., "network" "innovation") that has instantiations in a variety of disciplines as the object of formal understanding and modeling.

Crutchfield seeks to understand the origins of evolutionary *innovations*. How has evolution led to the development of new biological forms and functions over the millennia? Why have periods of evolutionary stability (where few phenotypical changes are recorded) been interrupted by periods of rapid innovation (with the emergence of new forms, functions, and species)? Crutchfield does not analyze the fossil record, nor does he experiment with gene distribution in rapidly growing fruit fly populations. Instead, he develops computational systems that emulate innovation in complex evolutionary processes.

In Crutchfield's view, a mathematical theory of evolutionary dynamics seeks to "articulate a conceptual model of phenomena that range from the molecular scale of genes to the geological scale of macroevolution." To do so he investigates the computational qualities of *innovation* in information systems of different kinds and scales that are reminiscent of micro and macro evolutionary processes in the real world. He does not seek to establish a causal relationship between phenomena at these different scales, but rather parallelisms in the way *innovation* behaves.

Integration mechanism in a *conceptual-bridging* approach

Three epistemic moves are frequent when individuals in our study employ a *conceptual-bridging* approach: identifying a *bridging motif;* establishing cross disciplinary *analogies;* and *translating* disciplinary constructs to inform (and be informed by) a formal mathematical model of the motif.

Bridging Motif "Innovation" is implicated in micro-phenomena studied by molecular biology and macro-evolutionary phenomena typically studied by paleontology. As a unit of analysis, "innovation" provides a level of characterization from which these disparate phenomena can be brought together in a single descriptive account expressed in mathematical algorithms. Crutchfield's algorithms formalize computational systems in which innovation is followed by equilibrium across a range of virtual scenarios.

Analogy When using this approach, researchers identify bridging motifs with ease and refer to analogy as a key mechanism to link disciplines—often extending their links across the natural/social sciences divide. In a study of market behavior, Mark Newman [SFI] bridges economics and biology by examining how the concepts of "efficiency" and "equilibrium" played out in both systems. Doyne Farmer [SFI] describes a discussion about the markets and thermodynamics with a physicist and a computer scientist in similar terms:

> How does entropy figure into markets?...If we compare a physical system where we have … molecules bouncing into each other, interacting, and where the measurable properties are things like pressure and temperature, how do we compare that to an economic system where we have agents who are interacting via buying and selling and measurable properties are things like the price and the volatility of the price? … An analogy to temperature is a bit like the random components of the agents' decision-making processes. You assume these agents are doing some coin flipping, generating some random numbers to make their decisions…that creates something that's like entropy and physical systems. [We are trying] to make those statements I just made precise [in order] to understand the analogies between the two and to see whether thinking in those terms provides us with some helpful ways to think about questions like, "How efficient is the market?"

When studying Renaissance history, John Padgett [SFI], develops "autocatalytic network" models[2] to shed light on the intellectual, political, and economic factors that gave rise to the Renaissance in Florence (1300-1500). He does so after observing structural parallelisms between dynamic chemical networks and historical social networks. He points out:

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[2] This was originally a chemical theory based on the work of Manfred Eigen and Peter Shuster (Fontana's advisors).

> You'd be amazed how much similarity there is in just [their] architecture….between pictures of artificial chemical data and how they changed over time, and pictures of actual historical Florentine networks and how they changed over time.

Translation While analogies enable researchers to link comparable phenomena across disciplines, analogies alone are insufficient for interdisciplinary integration. Farmer explains:

> Our belief is not that these analogies fit perfectly, just that they provide a good entry point to begin thinking about the other system. You just map over the whole set of ideas and trends, identify the pieces that look kind of similar, map it on, see how that fits. If it doesn't fit, then you start tinkering with parts to see what you've got to change to make it fit.

"Tinkering with parts" to find an accurate fit between analogous concepts, or re-representing a concept like "evolutionary innovation" or "social network" in the language and modes of thinking of non linear dynamics involves an effort of translation. If analogies allow researchers to build initial links, translation enables them to integrate epistemologies. For example, Padgett operationalizes voting practices in his model of the political life of Renaissance Florence:

> 'cv' [sic. a variable in his model] is 'cost of voting', analogous to cp the cost of partisanship. Unlike the cost of partisanship, I assume the cost of voting is quite low cv << cp. I don't assume cv = 0, however, because I presume there is some spatial distance beyond which voters simply don't care. (Padgett, 2000)

Padgett's translation involves more than the adoption of an algorithmic language to describe historical phenomena; it also requires adopting a logic by which voting practices and human relations are stripped of their nuance and redefined as sharply delimited and quantifiable variables. When re-represented in such functional models and as computer code, Florentine voting practices can be "manipulated" to explore how patronage networks and policies may have interacted to yield republicanism at the time. Translation efforts of this kind are common among informants advancing sophisticated mathematical or computer-generated models to examine patterns across biology, physics, social science, and art.

Assessing insights in *conceptual-bridging* work

Researchers reveal a variety of epistemic values when appreciating or critiquing their ID attempts. Most typically, they value models that are *elegant* and yield *predictive* and *generalizable* understandings. "You learn a few basic principles, and when you are confronted with a new problem, there is a way of working out an answer," claims Newman, highlighting a model's generalizability. He adds:

> Many other phenomena worldwide operate as networks. So, for instance, if you know that a particular [social] network has a bipartite structure—i.e., a two-mode structure such as the groups and the [individual] people—then there are various predictions you can make about it, predictions about the average number of degrees of separation between pairs of people and about the average number of people with whom each person sits on boards

In the best-case scenarios, Crutchfield proposes, algorithmic descriptions of constructs like innovation allow scientists to predict that, "there's going to be a new biological phenomenon. You're not sure about it. You go to the experiment. And lo and behold, it's there."

These researchers value models that adequately "rip out" the complicated nuances and specificities from the disciplinary problems that they study. Crutchfield explains:

> The work I'm doing in biology is very theoretical, mathematical. For me, as a physicist, there are certain kinds of questions that are very interesting about this. I'm specifically interested in evolutionary dynamics, how it is that the biological complications of Darwinian and neo-Darwinian theory get reduced to describe how populations and structures evolve… the goal is to come up with the simplest possible model that describes the phenomenon. You rip most everything out. There's even an art to doing it, you rip things out until you've got what you can claim are the essential mechanisms—the minimal set that still reproduces the phenomenon you're studying. And that means you've got a small model, a packed, concise model from which you can predict various things that are seen experimentally.

When building models of complex biological processes, Newman notes, "the first problem one faces is to specify what aspect of reality is being modeled. Modeling a *true* genetic regulatory network in a predictive sense is clearly impossible." Padgett agrees by highlighting "elegance" as a key criterion in his work:

> What I mean by elegance is the ability to explain coherently, highly heterogeneous phenomena. So the more heterogeneous the phenomenon, the more elegant an argument would be. A classic physicist could have uttered that sentence that I just uttered. Most physicists would agree … explaining heterogeneity with simple principles. That's really what it's all about.

For most researchers embracing a conceptual-bridging approach, gains in predictive power, generalizability, and elegance are associated with increased difficulties in fit between their models of a bridging motif and the particular instantiations of the motif in single disciplines.

Physicist Murray Gell-Mann [SFI co-founder] appreciates models like the ones here described because they encompass a great amount and variety of information, yet he is concerned by the fact that models can be simplistic, leaving nuances and whole dimensions of complex problems aside. Gell-Mann calls for greater fit as a criterion against which to assess these models, yet he also recognizes the challenge involved:

> There's a great puzzlement as to how to compare these models with the data. If they fit the data, if they were to fit the data perfectly, it would be embarrassing. Why would such a crude model possibly fit the data? But fitting data is usually the best way to judge a theory.

Gell-Mann's proposed solution involves reaching a delicate balance between empirical richness—typical of disciplines like biology, anthropology or paleontology—and the formal rigor of computer science and non-linear dynamics:

> Look for patterns, regularities, middle level theory, phenomenological principles of some sort that are known to hold or that you discover in the data, and look for those in the model. Try to find a model such that as you continuously proceed from the real situation with greater and greater and greater simplification, these regularities persist. Then you can explain them in the simple model. That explanation might still be valid in the much more complicated reality.

Ensuring the fit of their models is a central concern among informants when characterizing a conceptual-bridging approach. Crutchfield welcomes the opportunity to carry out “real, in the lab experiments on evolution to see if the theories are right.” However, when experimental designs stand across disciplinary borders they typically require adjustments by the disciplines involved. He explains:

> Right now we’re engaged in trying to convince an experimentalist to do the experiments that are simple enough that our theories are applicable. And we’re also attempting to go half way towards them, adapting some of our existing theories to deal with some of the complexities of the experimental world.

Like Gell-Mann, Crutchfield proposes a more balanced integration of theoretical and experimental approaches typically stemming from different domains:

> Biology is 80-90% experiment. In physics, it is more balanced, though there remains a tension between experimentalists and theorists. One condescends to the other. By comparison, with biology, though, I now appreciate that overall there is a pretty healthy interaction between theory and experiment in Physics.

In sum, this first approach to interdisciplinary research attempts to explicate single, principles, mechanisms, or laws (e.g., innovation) that can account for phenomena that are typically studied in a broad variety of disciplines. To integrate disciplinary views, experts seek analog constructs across disciplines (e.g., network, innovation) and formalize them to develop a unifying model. Epistemic values such as predictive power and generalizability, and elegance and simplicity guide these researchers’ efforts to validate their work. In turn, their main challenge lies in establishing the empirical fit of their models, since formalization demands stripping the complex real phenomena from nuance and detail.

II. A comprehensive approach to interdisciplinary work

> I have a professional interest in the evolution of adult lactose tolerance—why some of the world’s adults can drink milk and most cannot. So you go from that simple question which sounds like it’s a physiological question, which becomes a genetic question, and you go from genetics to really having to look at the cultural history of society, the archeology of what people did with cattle when and where to even the interpretation of ancient text rich in

> cultural meaning to understand how people's attitude toward milk have changed over time, when and where and under what circumstances. (Durham, 2002)

Overview

Like Crutchfield, William Durham [HUMBIO], is interested in evolution and works at the crossroads between natural and social domains. Yet his approach to interdisciplinary integration differs from Crutchfield's in informative ways. Durham views lactose intolerance at the intersection between culturally mandated behavior and the genetic traits in a particular population. "Cultural mediation" [as he describes the interaction] occurs whenever a cultural difference in memes[3] within or between populations creates a behavioral difference that in turn causes differences in the reproduction of genotypes" (Durham, 1991, p. 226).

Durham's work illustrates what is best described as a *comprehensive* approach to interdisciplinarity. He does not bring disciplines together by focusing on a unifying concept, principle, or mechanism (e.g., innovation) thought to account for a variety of analogous phenomena typically studied by different domains. Instead, he seeks to produce a complex explanation of a phenomenon - in this case, lactose absorption- whereby aspects of the phenomenon, typically studied by different disciplines, are considered in dynamic complementary interaction. His work is informed by insights in areas as varied as genetics, public health, archeology and mythology, which are interwoven in a multi-causal account, playing distinct evidentiary and explanatory roles.

Integration mechanism in a *comprehensive* approach

Three epistemic moves seem key to a comprehensive approach to interdisciplinary work: *defining a multidimensional problem*, *reframing disciplinary findings*, and *articulating complex accounts*.

[3] Memes: unit of cultural information that can be transmitted from one mind to another. The term was coined by Richard Dawkins (1976) in *The Selfish Gene*.

Multidimensional problem Durham seeks to understand how cultural and biological processes interact in the evolution of human differences. Disciplines that study human biology (e.g., physiology, genetics, biochemistry) inform him about the reproductive success of particular genes and the process of lactose absorption . Disciplines that study human cultures (e.g., anthropology, history, art, and mythology) inform him about longstanding practices of milk consumption. In Durham's view, "It has become increasingly apparent that the full explanation of human diversity requires attention to both biological and cultural processes" (Durham 1991).

Carol Boggs [HUMBIO], frames the study of incest taboo in comparable multidimensional terms:

> [Defining the problem as a bio-social one] allows one to see where cultural evolution interplays with biological evolution. So what you've got coming from the anthropology side are ideas associated with kinship, ideas associated with ethnography, ideas associated in essence with how cultures are put together and what culture is. "What culture is," is something biologists are always tripping over. On the biological side you've got issues of inbreeding, depression, and the biological effects that that has. You've got some neurobiology about how the brain is wired, you've got ideas about the possible role of genes and behavior and so on. It is a web of relationships.

Reframing Once problems of study are defined as multidimensional, an ongoing process of reframing —the second integration mechanism -- enables researchers to transition across disciplinary boundaries. Reframing involves placing claims or findings emerging from one disciplinary inquiry in the context of another discipline as hypotheses for further exploration. For example, Durham explains "If lactose absorption is a genetically encoded and inheritable capacity in some human populations, it must have presented an evolutionary advantage at some point in the past." He then turns to study the past aided by population genetic analysis of this condition and a close examination of bovine themes in Hindo-European myths (e.g. nourishing versus bellicose representations) as indicators of ancient milk consumption practices. His regional analysis of ancient myths sheds light on how themes varied as a function of latitude. Understanding physiology and biochemistry enables him to detect the role of lactose in enhancing the absorption of calcium from fresh milk in the small intestine.

> So what really started as a physiological question became a genetics question became a cultural question and became a question about interpreting text and all the problems of translation and innuendo and meaning that this [process] entails.

Articulating comprehensive accounts The third and final epistemic move in comprehensive interdisciplinarity involves the integration of insights into a coherent explanatory/descriptive account -- one in which multiple causes or factors typically studied by different disciplines are brought together complementarily to advance understanding as a whole. Durham explains "how and why adult lactose absorption has evolved in some human populations and not others" (Wilson, 1998, p. 240) as follows:

> Using data obtained from samples of human populations in Europe, Greenland, Western Asia, and Africa we have seen that the prevalence of adult lactose absorption co-varies with latitude in a pattern just opposite to that of incident UV light radiation. This finding, together with other evidence concerning the physiology of mineral metabolism, supports the hypothesis that the genes responsible for adult lactose absorption have evolved in high frequencies in populations that (1) have a longstanding tradition of dairying and fresh milk consumption and (2) live in environments of low ultraviolet radiation where vitamin D and metabolic calcium are chronically deficient (p. 279).

Taking a more reflective stance, Carol Boggs [HUM BIO] also describes such multi causal explanations in dynamic terms:

> You need multidimensionality and cohesiveness. It can't be a jigsaw puzzle just stuck together; it's got to have blending between the two [disciplines that study culture and those that study biology] ideally. It's got to have attitudes and conclusions that are drawn from one extreme end of it [i.e. studies of culture] blending into the attitudes and conclusions drawn from the other extreme end of it [studies of biology].

In short, by defining problems of study as multidimensional and placing them across disciplinary lines, researchers embracing this approach set the stage for an inquiry that is defined by its ongoing process of reframing and its goal of creating complex multi-causal accounts. As Durham described it:

> You don't conceive of it as a bridge [between disciplines]. I just simply started with the innocent topic of what explains human diversity with respect to milk drinking ability, and look what happened!

In comprehensive interdisciplinary efforts, researchers like Durham capitalize on the complementarity (rather than on the analogy) between disciplines.

Assessing insights in *comprehensive* work

When referring to the desired qualities of their work, these researchers typically value *"comprehensiveness"* (thus the descriptor of this approach to integration) as well as *explanatory* and *descriptive power*. Their challenge involves the lack of available knowledge to draw upon in neighboring disciplines and the time required to examine multiple areas of knowledge in enough depth.

Researchers embracing this approach recurrently refer to the importance of identifying appropriate disciplinary perspectives to leverage or enrich our explanations. "Science has done itself a disservice by the one-parameter approach," noticed Fernald [HUMBIO]. With an example of bird migration he illustrates:

> For a long time people said they could show pretty convincingly that birds migrate using the sun. Bill Evans--a scientist at Cornell, who studies this—[typically] puts all his pigeons into his truck, drives to nowhere and lets them go and fly back. One day he had driven three hundred miles and was going to let them go, but it was overcast and he didn't know what to do. He let them go and they flew in all sort of different directions. He was completely baffled. A friend who was a geologist, said, well, you happened to let them go in a place that was a significant magnetic anomaly. So, these birds may use light, or they can use magnetic fields. They can actually use air pressure. That opened his mind to the parametric exploration of their combinatorial powers. When it's overcast, the birds just turn on their magnetic system. So in some sense, that creativity was forced upon him to sort of have multiple interpretations of things and consider a spectrum of parameters rather than just varying one at time.

Taking a similar stance in her work in medical ethics, Renee Fox critiqued contemporary American impulses toward international Bioethics for failing to approach the question of medical practices and beliefs more comprehensively. “Bioethics is becoming international, yet I don't think [it] is tackling the social and cultural differences well enough,” she worries. She contrasts her standards for comprehensiveness to her colleagues’ “drive-by ethnographies” of Chinese sentiments about medical ethics that “made no reference to Confucianism, or to Taoism,” thus failing to explain how medical values were “deeply rooted in two thousand years of Chinese culture” (Fox & Swazey 2002). In Fox’ view, by incorporating elements in the history of Chinese civilization as relevant factors, a more comprehensive explanation is advanced (Glicksman, Messikomer & Swazey, 2002).

Yet in the eyes of these researchers, comprehensive work comes at a cost. All too often, as they reframe findings into hypotheses to be explored in other disciplines, they confront scarcity of knowledge about their problems in the particular discipline being explored. When hypotheses stem from findings in neighboring disciplines, it is not uncommon to find that not many studies are available addressing the issue at hand. Clearly the multidimensional problems of study that characterize comprehensive interdisciplinary work hold different levels of centrality in the disciplines that are used to account for them.

For example, Bill Durham confronts lack of crucial data on age specific fertility in El Salvador, where in the face of scarcity, poverty, and disease, the population continues to grow,

> Okay, we have a population growing. Well, people have modeled that. And we have these different models… some on consumption….We get birth rates and death rates … But who knows what the age specific fertility is in El Salvador? I don't know what the total fertility for a woman is in El Salvador…. you can find it, if you have a month to look.

Lack of available scholarship in neighboring domains leads to a fundamental challenge associated with comprehensive interdisciplinarity. Often, Durham claimed:

> The materials just aren't there to support the kind of systematic thinking to really take a problem or a question like that and really go all the way to wherever it leads. This kind of research does not lead you down comfortable paths. It leads you immediately into your own ignorance. And that is great, challenging, and fun and also sometimes very inefficient.

Researchers express concern about the risk represented by this kind of inquiry of becoming a time consuming renaissance enterprise. In Durham's words:

> What's so frustrating to me in looking back on that book [Co-evolution] is that it took a year to do each chapter. Literally a year because you had to gain expertise and familiarity with times, jargon, theory, principles, applications, and precedent literature in so many different fields. You have to equip yourself as you do this. It's enormously challenging.

Philosopher Glenn McGee illustrates the challenge of time. He describes reviewing the work of a colleague in anthropology whose analysis took so long that the practices described by his work had been transformed by new technologies by the time his book was ready for publication.

In sum, a comprehensive approach to interdisciplinary research seeks to describe and explain multiple dimensions of a complex topic by articulating insights from multiple disciplinary contexts. Disciplinary integration capitalizes on the complementarity of disciplinary perspectives where insights stemming from one discipline raise questions or hypotheses that can best be explored through alternative disciplinary paths. Multiple acts of reframing culminate in an integrative multilayered account of the topic under study. Comprehensive integration is modeled after modes of thinking at that are typically present in empirical and broadly encompassing disciplines such as anthropology, sociology, geography, history, and naturalistic biology. Epistemic values held by researchers to assess this type of work involves comprehensiveness and explanatory richness. Their challenges include lack of relevant available scholarship in selected domains as well as the extensive time requirements associated with a comprehensive standard.

III. A *pragmatic* approach to interdisciplinarity

> It is extremely problematic that the early stem cell research currently underway has been driven by small business, because at this early stage the only real resources that small stem cell companies can hope to build up are patents. If stem cell research is tied up at this stage by patents and licensing agreements, even if those patents are held by universities, the effect will hamper research, but moreover will tax any federal dollars for stem cell research in an unacceptable way. At this point one could reasonably argue that as much as 30-50% of the federal funding for stem cell research would flow indirectly to small stem cell companies through the fees that they can assess to any funded researcher.…Whether or not there is federal funding of therapeutic cloning, there must be more oversight over nuclear transfer technologies and specifically over the control of those technologies by a few people in small businesses. (Glenn McGee, 2002)

Overview

Glenn McGee, a philosopher at the Center for Bioethics in the University of Pennsylvania, examines the ethical, legal, economic, and social issues associated with biomedical research, especially reproductive genetics and stem cells. McGee's approach to interdisciplinary work, illustrated here by what I call *pragmatic interdisciplinarity*, differs from Crutchfield's and Durham's in important ways. McGee does not seek to model analogical patterns underlying complex systems, nor does he hope to reach a comprehensive characterization of the ethical dilemmas of stem cell research. Rather he seeks to offer prompt, informed, and impact-full advice to lawmakers about the current status of human embryonic stem cell patenting and the potential consequences of lenient intellectual property adjudications. His work is marked by a clear sense of purpose and a strategic, often productively eclectic selection of disciplinary insights.

Integration mechanisms in a *pragmatic* approach

Two distinct epistemic moves characterize the pragmatic approach to interdisciplinary work evidenced in our data: researchers begin with a clear sense of the *target outcome*--e.g., legal advice, a new medical technology, a computer artifact--which informs their disciplinary selections. They approach their targets by borrowing, often eclectically, from two or more domains through *strategic back-filling*. Their solutions are assessed against standards of relevance, viability, and effectiveness.

Target outcome McGee begins his research with a clear goal in mind: to inform intellectual property policy about what happens when the technology and *know how* for human embryonic stem cell research is made eligible for patenting. His immediate goal defines not only the form in which his findings are to be communicated (they need to be understandable to the public as well as to their government representatives) but also what constitute effective ways to accomplish the task.

To begin with, McGee examines the technological procedures involved in isolating and cultivating pluripotent human embryonic stem cells as well as scientists' perception of the potential of these cells for basic and clinical research (Caplan et al 2002). He asks: how do patents define the extent of intellectual property vis-à-vis the materials, forms of manipulation, and methodological uses of stem cells? Who owns these patents and what incentives might they have to maximize their use in therapeutic research? His analysis excludes theological or philosophical considerations, to focus empirically and strategically on US-issued patent claims on human embryonic stem cells up to the time in which the G .W. Bush administration limited federal funding to research employing available stem cell lines.

Target outcomes provide researchers with a clear compass for strategic selection of disciplinary inputs and research design. For example, Joseph Vacanti [CIMIT]characterizes his problem focus in artificial human tissue engineering as follows:

> My research is problem driven. It is not trying to discover something or trying to take a tool and figure out a way that I might take advantage of it. It is completely problem driven. Once I knew about the silicon micro machine [a technology developed at the MIT Draper Labs], I knew of its advantages and knew we could do something with it. But there were certain unknowns [about how to make the technology work with capillary tissue] and therefore you had to do research. The collaboration was set up specifically as a solution to a major problem.

Similarly, Arthur Caplan [CB-UP Director] comments:

> If you see it the way I do, [Bioethics] has to be interdisciplinary because you're using different skills, different approaches to solve a problem. The old model for this is you come more like a plumber with a tool box to figure out why the drain is stopped. More than saying I'm going to do what somebody does whenever they face a problem in chemistry, which is to do the exact same thing [to use a common set of disciplinary skills] again and again, knowing what to do.

Deb Roy [ML] too emphasizes the central role of target products in guiding her experiments. Her research explores the relationship between early word learning and the physical contexts and experience that inform such learning. To address this problem she builds model machines that bring together writing computer code, psycho-linguistic theories and robotics to test ideas.

> I build as a way to think, so I oftentimes can't imagine how a theory or a model is going to play out because there are too many interactive parts, and so rather than trying to predict or trying to theorize or build models on whiteboards, I'd rather just start building, period. So building, for me, is a way to bring some sort of model to life and see whether it actually holds together given those assumptions.
>
> That takes you along a certain path in terms of the type of questions you're more likely to ask in a situation, so when it comes to psychology, to me the most promising way to think about how infants are solving such and such a problem is to build a model of that and then throw realistic data at it and see how it breaks… poke at it.

Strategic back-filling Echoing this view, Vacanti sheds light on a second characteristic move of pragmatic interdisciplinarity: its strategic backfilling orientation. Strategic backfilling involves weighing potential disciplinary contributions directly against the expected target outcome. Strategic backfilling calls for a productive eclecticism in which disciplinary insights are brought together to create an object, a recommendation, or an exhibit that "works." Vacanti's experiments are often designed as proofs of concept--an approach that he contrasts sharply with more canonical science.

> I skip many, many steps because I want to know, "is this a good idea or a bad idea?" So we try to Jerry-rig systems that will just try to answer that question. We try to do it carefully. But we skip steps. Sometimes scientists have a reductionist approach to innovation. You go from step 1 to step 2, step 2 to step 2a, step 2ai to 2aii, [thinking] if you do that eventually you're going to get there.
>
> Well, we do some of that, but we say: "We want to build a heart. How can we build a heart? Well, let's do this." Then, if it shows any promise, you can start to back fill. So we do a lot of leap ahead, back fill, leap ahead, back fill. Philosophically, you either think that's good or you don't. I think it's good. And the micro machining [at the Draper Labs] was that large leap ahead. We could see what happened, and, if it seemed like a sensible idea, then back fill while we move ahead. And that's what we've done.

Strategic backfilling permeates disciplinary choices made within pragmatic interdisciplinary approaches. For example, in Caplan's view, the type of problem studied guides the relative prominence of singular disciplines:

> I think there are times when the law should be the discourse. For certain issues [e.g. policy on informed consent] you do want to know what really is the legal framework in which you are operating. And some other issues like, should we ban cloning--starting with the law is really not a good idea, it's [that] you really need to think philosophically about what is cloning and why would it be bad and then you could make a law later. Sometimes the lawyers get there prematurely before there is consensus about the values, but in other places there's a lot of consensus about the values and you don't need to dig up the same old holes again. I mean you could do it again as an academic--basic work activity.

Assessing insights in *pragmatic* work

Given the focus of this approach to interdisciplinary research on target outcome and backfilling, *relevance* of the interdisciplinary problem of study and *effectiveness* of proposed solutions emerge, understandably, as dominating epistemic values in these researchers' discourse. For instance, McGee roots his attention to relevance in the Deweyan tradition of "selective emphasis."

> For example, the most important insight, in my view, of pragmatism, is one that's lost among most bioethicists. It is the question of which problem one ought to study and to what degree one should emphasize that problem relative to other problems in one's sphere of work--what Dewey calls "selective emphasis." This is a very, very useful insight that Dewey has about how knowledge works and about how people come to think about value. Pragmatism means being involved publicly, recognizing that the relationship between facts and values is not static, and I guess also knowing that there is an inherent weakness to arguments that are based on eternal verities.

Joseph Vacanti exemplifies this commitment to relevance. He assesses his work against the standard imposed by the pressing problem of lack of available human organs for transplantation. "All the original work that I have done professionally is completely driven by my patients' needs. It has never been because of a piece of science or a piece of technology."

In a sharp critique of bioethicists' recommendations promoting living will policies, Caplan also calls attention to the effectiveness of solutions as a criterion to assess the work.

> There are philosophers fighting for individual rights by God, the autonomous individual to be fully self-governing even at the time of greatest vulnerability…They created a whole department in the FDA … to ensure that every State would have a living will policy, and all of this without ever conducting a study to see if the advanced directives work. Not one!

Nicholas Negroponte [Former Director, ML] further emphasizes effectiveness as a criterion to assess interdisciplinary research that is destined to have an impact in industry. He highlights the importance of effective communication with the sector—a key audience for their work.

> Explaining a machine or teaching an algorithm to a sneaker manufacturer is an interesting phenomenon. You have to realize that the sneaker manufacturer probably has a Ph.D. in material science and may have worked at Bell Labs previously, and he's a smart guy. So it's not just schmoozing, and it's not just one way [technical transfer], and it's not just technical in your

> discipline. It's being able to communicate the importance of ideas to bright sorts of people at a *Scientific American* level, in a focused way.

Yet while a strong focus on products and target outcomes and a close relation with relevant audiences emerge as defining qualities, knowledge validation in this kind of work is not without challenges. Some researchers worry about the problem of becoming too pragmatic—too outcome oriented.

Bruce Blumberg [ML], expresses concern about the opportunities lost in pragmatic research—opportunities to understand a phenomenon in a deeper way--and beyond product development. He remembers a critique of research on modeling animal behavior:

> Is this going to help me understand rat behavior better? Because if it is, then you haven't accounted for--x, y, and z, a list of standard things that rats do. And if it's animated characters, well, that's great, but that's not of interest to me.

Blumberg expresses concern about approaches to interdisciplinary work that fail to capitalize on the explanatory and experimental opportunities afforded by animal modeling research.

In sum, a pragmatic approach to interdisciplinarity is often employed to offer viable solutions to problems perceived as important in the social, political, medical, and technological realms. In this case, researchers identify a target outcome (e.g. a policy recommendation on stem cell research, new musical technology) and select constructs, skills, and tools strategically from a variety of disciplines to advance a solution to the problem at hand. When compared to standards of viability, efficiency and effectiveness in getting the outcome to "work," measures of comprehensiveness or generalizability take a distinctly less prominent role.

To conclude: three approaches revisited

The three approaches proposed embody distinct ways in which researchers in our study framed and pursued interdisciplinary inquiry problems. Each one is associated with preferred vehicles to integrate disciplinary perspectives, and favored orientations vis-à-vis knowledge validation. Inquiries framed as *conceptual-bridging* endeavors capitalize on analogies across domains to advance a mathematical model or theoretical account of phenomena like network behavior or innovation. They emphasize a clear definition of a bridging motif as an object of study, the examination of cross domain analogies, and the translation of findings into a common language or form of representation that works across domains. Research outcomes tend to be measured against standards of elegance, predictive power, and generalizability, and face challenges of fit between complex generic models and particular data stemming from participating domains.

Inquiries framed as *comprehensive* investigations exhibit a different quality. Focused on a multidimensional quality of their objects of study, this form of interdisciplinary integration capitalizes on the complementarity among disciplines. In it, researchers transcend the limitations of one discipline by *reframing* its findings as questions in new disciplinary contexts. Comprehensive interdisciplinary outcomes take the form of hybrid multi-causal explanations that integrate factors stemming from a variety of domains. Accounts are assessed by their all-embracing explanatory or descriptive power.

Pragmatic approaches, in turn, focus sharply on expected outcomes, integrating disciplines through a process of productive backfilling. Outcomes are judged against standards of relevance and effectiveness. Leading concerns involve an emphasis on immediate problem solving and product development that may underplay fuller explanations.

As ideal types, the three approaches here described help us visualize relevant distinctions among interdisciplinary research enterprises--the strength of one often embodying the weakness of another. For instance, the power of generalizability reached in conceptual-bridging work contrasts sharply with the limitations of pragmatic interdisciplinary research in generalizing findings beyond its specific intended outcomes and audiences. The effectiveness of a pragmatic approach contrasts with the time-consuming nature of comprehensive research, which in turn tends to offer more powerful explanations than its pragmatic counterpart. Each approach embodies preferred forms of cognitive advancement. Researchers are likely to choose among approaches or combine them, depending on the overall purpose of their inquiry. In fact it is the very framing of their problems of study that drives the preferred approach and related mechanisms and standards of acceptability.

The three approaches to interdisciplinary research emerging from my analysis embody dynamic systems of thought in which the purpose, mechanisms of integration, and validation criteria are defined and adjusted in relation to one another. Disciplinary perspectives are not equally represented in each approach. The relative dominance of particular disciplines in each case is determined by the purpose of the research itself and in turn shapes the overall enterprise. For example, to explain fundamental commonalities across phenomena typically studied by different disciplines, a conceptual-bridging approach invites the use of formal languages most typical of mathematics and computer science or even analytical philosophy. With formal domains as dominant forces, standards of elegance and generalizability are, understandably, at a premium. Comprehensive interdisciplinary work, on the other hand, places a premium on disciplines like anthropology or evolutionary biology— i.e., more synoptic domains which naturally invite multiple disciplinary sources of evidence. It is not surprising that descriptive richness and explanatory power together with comprehensiveness are the preferred criteria within this approach. Finally, pragmatic interdisciplinary work, marked by its emphasis on problem solving and product development, prioritizes disciplines (or professions) such as law, public policy, graphic design, and technology. In this case again, determining that a solution "works" is valued more than generalizing beyond the particular case or explaining *why exactly* it "works" in that particular way.

The approaches here proposed are informed by highly innovative work that bridges social, natural and technological domains. By concentrating our sample on informants who were charting novel disciplinary combinations (e.g. in artificial human organ creation, legislation of stem cell research), we were able to capture these researchers' thinking at the moment in which both mechanisms of integration and standards were being created and in some cases explicitly examined. Our discussions focused on work being done at the time of our interviews, thus revealing vivid images of researchers' epistemic efforts stemming from their experience of "building their methodological and validation criteria boats while sailing." Less attention was paid in our interviews to important standards of validation that benefit from hindsight- e.g. generative capacity of a study to open up new lines of research. Further studies may shed light on the validity of the approaches proposed beyond the confines of our sample. For example, a further quantitative study could examine the degree to which forms of problem definitions, disciplinary dominance, mechanisms of integration and standards of validation are clustered in ways that support or reject the predictions afforded by each proposed approach.

Most importantly, a parallel study of interdisciplinary research at the frontier of knowledge production primarily driven by literary or artistic sensitivities is likely to reveal additional mechanisms and standards of validation. Arguably, one could expect an artist's rendition of possibilities and perils of human stem cell research to integrate genetics and the visual arts through a metaphor that captures something essential about contemporary choices vis-à-vis human biology (e.g., imagined freedoms). An artistic rendition of the metaphor would present itself as an open invitation to reflection—one in which standards of evocative power and multiplicity of meaning are likely to overshadow criteria like generalizability, explanatory power, or effective problem solving.

Understanding the intellectual demands of interdisciplinary work in its various forms will enable us to target educational efforts to guide the young to become shrewd interdisciplinary researchers themselves. Researchers in our sample described their encounters with multiple disciplines during their graduate and post graduate training. They characterized the process of decoding their mentors' and colleagues' epistemologies (preferred units of analysis, standards of validation, discursive forms). Yet they also saw themselves as embracing the complex task of integrating perspectives on their own nad with little support. Recognizing that disciplinary integration is a tall cognitive order, the results of this study inform faculty interested in fostering students' interdisciplinary understanding and research capacity. They do so by making the epistemic and cognitive dimensions of quality interdisciplinary work visible, and particularly emphasizing how disciplines come together to advance understanding productively.

Ultimately, understanding the distinct intellectual mechanisms by which experts cross disciplinary boundaries sets the foundation for a much needed expert dialogue across the sciences and with the humanities. Such a dialogue is more likely to progress in the micro cosmos of particular knowledge initiatives than under a grand theory of integration. Yet to be productive, such dialogue must recognize the patterned diversity of aims and approaches that characterize interdisciplinary work--thus sidestepping the mutual accusations of reductionism and irrelevance that have marred academia for decades (Snow 1993).

Table 1. Expert sample by institution and main disciplinary affiliation

Institution and number of faculty/experts interviewed	Informant	Main disciplinary affiliation of informant
Bioethics, University of	XUP01	anthropology/communications
Pennsylvania	XUP02	history/philosophy
[BioE]	XUP03	sociology
N = 6	XUP04	philosophy
	XUP05	sociology
	XUP06	philosophy
CIMIT	XC01	engineering
N = 7	XC02	medicine (cardiology)
	XC03	physics (medical instruments)
	XC04	medicine (cardiology)
	XC05	medicine
	XC06	medicine (pediatric transplant surgeon)
	XC07	engineering
MIT Media Lab	XML01	computer science
N = 13	XML02	computer science
	XML03	computer science/art
	XML04	linguistics/comparative literature/psychology
	XML05	history / technology in education
	XML06	computer science
	XML07	computer science/ science journalism
	XML08	computer science/artificial intelligence/ poet
	XML09	engineering (electrical)
	XML10	history/computer science
	XML11	computer science
	XML12	music (composer + performer)
	XML13	computer science
Santa Fe Institute	XSF01	physics
N = 15	XSF02	biology/genetics
	XSF03	physics
	XSF04	physics
	XSF05	liberal arts/ marketing
	XSF06	finance/economics
	XSF07	physics
	XSF08	liberal arts
	XSF09	biology/physics
	XSF10	chemistry
	XSF11	English
	XSF12	history /sociology /public policy
	XAS01	music / physics
	XAS02	film making/media (video artist)
	XAS03	music
Xerox Parc	XRX01	audio engineering/design
N = 9	XRX02	computer science/ theater /fine arts
	XRX04	communications research
	XRX05	architecture/computer science
	XRX06	engineering/film/education
	XRX07	engineering
	XRX08	art/poetry
	XRX09	design/technology
	XRX10	writer/artist ("media art")
	XRX11	music (composition)/art/engineering

Human Biology,	XST04	health policy
Stanford University	XST07	neuroscience
[Hum Bio]	XST11	ecology
N =5	XST12	anthropology/biology
	XST18	developmental psychology

XAS Artist collaborators at Art and Science Lab, Santa Fe, NM

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