Building Bridges Across Disciplines:

Organizational and Individual Qualities of Exemplary Interdisciplinary Work

By

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Abstract

The expression “interdisciplinary work” refers to work that takes place at the crossroads of two or more disciplines. It denotes the way in which researchers and institutions organize professional life, as well as the particular nature of their intellectual enterprises. In this paper we examine institutional and intellectual dimensions of interdisciplinary work as described by innovators in five exemplary organizations. These institutions include the Santa Fe Institute and the Arts and Science Laboratory in New Mexico, the MIT Media Laboratory and the Center for Integration of Medicine and Innovative Technology in the Boston-Cambridge area, and the Research in Experimental Designs group at Xerox PARC in Palo Alto, California.

Interdisciplinary ventures in these institutions vary greatly in goal, scope, and type. For instance, the strategic alliance between art and technology may respond to an aesthetic motivation to critique our times or to a practical desire to address the needs of a society of the future. Interdisciplinary projects may enlist large teams of researchers or consist of a committed pair of thinkers examining society through a novel lens. Interdisciplinary collaborators may borrow from each other just enough to solve a particular problem, or they may immerse themselves in each other’s disciplines to transform them at the core.

This paper examines organizational qualities that support and hinder interdisciplinary work, as reported by the subjects in this study. It addresses the pros and cons of particular

types of institutional affiliations (e.g., permanent research staff in a centralized physical location versus networks of researchers coming together temporarily). It examines the strengths and limitations of research problem definitions (e.g., institutions that discover innovative problems and their solutions concurrently versus those who offer new solutions to old problems). Moreover, this paper explores the ways in which researchers organize their work to combine areas of expertise effectively (e.g., through collaborations and through the development of “hybrid” researchers).

At the individual intellectual level, the paper characterizes exemplary interdisciplinary workers as embodying a disposition toward curiosity, risk-taking, open mindedness and humility. We discern three commonly used strategies to bridge disciplinary divides (fluid integration, translation and explicit integration) and we identify the particular skills that allow researchers to navigate the interdisciplinary terrain (analogical thinking, common languages and metadisciplinary views).

The diversity of existing interdisciplinary ventures poses a challenge to those interested in making sense of this mode of knowledge production and proposing an integrative framework to describe it. Recognizing this challenge, we conclude this paper by suggesting promising lines of future research.

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I. Introduction

Decisive shifts in knowledge production permeate the turn of the 21st century. Advances in computer science, biology, and psychology have propelled unprecedented breakthroughs like the cloning of the human genome and the creation of "affective machines." The alliance of medical doctors, engineers, computer scientists, and molecular biologists is revolutionizing medical care through new, minimally invasive surgery technologies and artificial human tissue development. Working together, artists, architects, computer engineers, and anthropologists are developing early prototypes of computer-enhanced environments, which range from intelligent homes to electronic paper. In the arts, avant-garde exploration by new media artists draws on scientific and computational insights to celebrate and critique our times.

Each of these examples of knowledge production and product development has been born from interdisciplinary enterprises. In each case, traditional disciplinary boundaries are crossed and redefined, with increased borrowing and lending across disciplinary frontiers. The task of carrying out interdisciplinary work is intrinsically complex. It involves developing a meaningful dialogue among professionals who embody distinct disciplinary cultures (e.g., with regard to paradigms, values, and tools). It requires bringing together domains like computer science and art that often seem incompatible or respond to contrasting validation criteria. How do individuals and institutions organize their work to advance generative dialogue across disciplinary lines? What are the intellectual dispositions and cognitive strategies that serve interdisciplinary thinkers? What obstacles do organizations and individuals confront as they attempt to produce exemplary interdisciplinary work?

In this paper we report the results of a study of five exemplary interdisciplinary institutions. We began by examining interdisciplinary practices at the MIT Media Laboratory, a research institution founded in 1980 to explore the future of human–computer interactions. Our second study focused on the Santa Fe Institute in New Mexico. This research center brings together experts in physics, biology, chemistry, economics, political science, and history to explore their respective domains through the lenses of complexity and chaos theory. Also in New Mexico, our third case explored the Arts and Science Laboratory, an emerging research and performance institute geared toward uniting the arts and sciences by exploring the newest computer technologies. Our fourth institution, the Research in Experimental Designs (R.E.D.) group in Palo Alto, also seeks to merge arts and sciences to develop new experimental technologies.[1] R.E.D. is the research division of the Xerox Corporation. It works with individuals whose skills range from architecture and cultural theory to programming and video production. The last case in this series focused on the Center for Integration of Medicine and Innovative Technology (CIMIT) in Boston. This multi-institutional organization supports collaborations among physicians, scientists, and engineers to develop innovative medical devices.

[1] The R.E.D. group was closed after the organizational reconfiguration of Xerox PARC in early 2002.

Two main research goals guided our inquiry. First, we sought to understand how particular organizational structures and characteristics facilitate or impede interdisciplinary efforts among researchers and innovators working at the forefront of their fields. Second, we sought to discern the personal dispositions and modes of thinking that these researchers use when they are tracking uncharted interdisciplinary terrain. We developed preliminary answers to these questions by producing a case study for each institution.[2] In this paper we offer an integrative overview of findings across institutions. We begin by briefly portraying our research methods and procedures. We then report our results in two sections. First, we describe institutional strategies and obstacles to carrying out interdisciplinary work along organizational continua; then we characterize some of the individual dispositions and modes of thinking that researchers exhibit across various institutions. We conclude this paper with a series of research challenges to be addressed by future studies.

II. A Note on Methods

The institutions included in this study were selected as exemplary cases of interdisciplinary work. A series of formal and informal conversations with key informants in fields ranging from the arts and history to computer science and biology helped us identify potential candidate organizations. Through a series of screening interviews of candidate institutions, we selected the five organizations according to five

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[2] See http//www.goodworkproject.harvard.edu.

central criteria: (1) having been in existence for at least five years[3], (2) clearly stated research/product and educational goals, (3) continuity in the institution's direction (established by senior personnel), (4) existence of some formal or informal measures of success (including staff and student output available for review), and finally, (5) effort to bring together disciplines in novel ways. Institutions researching the history of science or biochemistry — interdisciplinary ventures extensively explored in the past — were excluded from our sample.

We conducted one-and-a-half hour, semi-structured interviews with 48 researchers at these institutions. Interviewees were selected on the basis of nominations made by leading members of each institution and by colleagues familiar with these organizations. Our interview protocol consisted of approximately 40 questions and addressed each institution's mission, organizational structure, strengths, and weaknesses. We also inquired into our subjects' early life experiences, professional training, and the beliefs and values influencing their interdisciplinary work. All of the interviews were conducted in person, audio taped, and transcribed. Following each interview, we produced a cover sheet which captured the initial impressions emerging from the interview and identified substantive highlights vis-a-vis our research questions.

Transcripts were examined by two researchers seeking to unearth subjects' descriptions of their individual work and thinking patterns, as well as the organizational structures that

[3] Being approximately one year old at the time of our interviews, the Art Science Laboratory was an exception to this criterion. We selected this group because its founders emerged in a preliminary study of new media art as holding long-lasting commitment and leadership in this field. Such study had also revealed the typically transient quality of art based institutions.

facilitate or impede interdisciplinary ventures. Analytical categories used to compare organizational strategies or individual characteristics emerged in part from prior analysis leading to the development of institutional case studies, and in part from a second analysis of coversheets and transcripts. During this phase, interpretations remained at a descriptive level, identifying and arranging participants' claims and self-reports. Attempts to produce explanatory interpretations or unveil tacit organizational and individual frames of reference were minimized in this initial phase of the study. Rather, we sought to capture the ways in which participants themselves reported their organizational experiences, actions, and individual thoughts. In what follows we present the results of our analysis, beginning with the organizational qualities portrayed by the participants.

III. Organizing Interdisciplinary Work

In examining our interviewees' references to the organizational structures that foster or hinder interdisciplinary work, it was the differences between organizations rather than the commonalities among them that called our attention. Institutions differed on three grounds: (A) They varied in the degree to which they were composed of permanent research staff in a centralized, physical location (i.e., "local affiliation") or of networks of researchers coming together temporarily to work on interdisciplinary projects while maintaining their primary institutional affiliation intact (i.e., "virtual affiliation"). (B) Institutions also varied in the way in which they defined the problems under study. While some organizations tended to create innovative problems and their solutions concurrently, others sought to offer new solutions to old problems. Finally, (C) researchers varied in the ways in which they integrated areas of expertise. In some cases they favored collaborating with experts in different fields. In other cases they preferred to become integrative experts, or “hybrid” researchers, working in two fields at once.

A. Local versus virtual institutional affiliation

A researcher’s institutional affiliation stems from his or her participation in the shared picture of the future the organization seeks to create. These visions may entail a world of unprecedented human-computer interactions, one of new forms of artistic expression informed by technology, one in which complex phenomena can be explained in non-reductionist ways, or one in which ailing patients are offered minimally invasive cures to their bodies’ illnesses. In dynamic organizations like the ones we examined, individuals’ senses of affiliation are rooted in the way people interact together around a common sense of destiny.

In some of the institutions under study, researchers manage to weave these affiliations together while sharing a regular space and stable cast of colleagues. The MIT Media Laboratory, for example, has a very stable group of faculty members who work in a common building (the Media Lab will soon be expanding to a second, adjacent building as a result of its growing programs and faculty). In hiring additional staff, Media Lab leaders are seeking individuals who intend to stay for an extended period of time. Similarly, the Arts and Science Laboratory faculty is stable. Its four members work together under the same roof several times a week, strengthening the human connections that bring them and their missions together. We describe these researchers as having a *local institutional affiliation* due to the local and stable nature of their interaction.

In contrast, researchers who have a more *virtual institutional affiliation* structure their interdisciplinary work through institutional visits and professional networks. These organizations feature members who assemble and adjourn frequently over relatively short periods of time and who have more than one institutional home. CIMIT, for instance, fosters mostly virtual affiliations. It seeks to stimulate and nurture collaborations among its growing and ever-changing network of researchers. These researchers' affiliation with CIMIT accounts for part of their work as permanent members of the Brigham and Women's Hospital (BWH), Massachusetts General Hospital (MGH), Massachusetts Institute of Technology (MIT) and the Draper Laboratories. According to our subjects, individuals typically spend one to two days per week on CIMIT projects in any number of locations.

Some institutions, like the Santa Fe Institute (SFI), have local and virtual characteristics in nearly equal measure. SFI is located in two large buildings and has about 10 permanent faculty members, several of whom have worked together for many years. In addition, SFI has an "external faculty" group of about 70 individuals who have a strong affiliation with the institution while maintaining their primary institutional homes outside of SFI. SFI hosts over 100 visitors each year; these individuals stay for periods ranging from a few days to a few years and are expected to make substantive contributions to the Institute's research. Generally speaking, SFI can be viewed as cultivating both local and virtual modes of affiliation.

No institution presented a pure case of local or virtual affiliation. At MIT, students are transient members of research teams, and cross-pollinate ideas and initiatives. At CIMIT, the Operations Committee is a stable, core managerial group that supports collaborations among researchers and guides the development of the organization by working within more local structures. Both models received praise and critique from our subjects.

Local institutional affiliation

Positive attributes of local institutional affiliation

1. Focus. People who are locally affiliated with their institutions can devote all of their time and energy to the institution's mission. This focus may be particularly important at interdisciplinary institutions, where the topics studied are by necessity somewhat unconventional (or at least untraditional). Pursuing unusual topics and combining disciplines may require a special commitment from individuals. They must transcend the common practices of traditional disciplinary settings — sometimes having to withstand harsh critiques from colleagues outside of these institutions who are solely involved in disciplinary work. Working on a daily basis in an organization that values interdisciplinary explorations as its core mission may constitute a safe haven for these practitioners. One Media Lab professor, Ken Haase, spoke to us about the need for an interdisciplinary institution to harness the "core energy" of its members.

> When Nicholas [Negroponte] and Jerry [Wiesner] first started the Media Lab in the late '70s / early '80s, they expected that within a few years

> there would be a lot of competitors. They were surprised when this didn't happen.
>
> One of the reasons it didn't happen is if you look around at the different programs that might be competitors, they are either one of two structures. One of the structures has something which is a center that is between departments … people from different departments are a part of it, but essentially you're getting their marginal energies and not their core energies.
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> The second case is some existing department declares a part of itself to be a media center or a media laboratory or whatever — so it's a part of computer science or it's a part of arts or it's a part of literature or what have you … and in that case it's part of the department, and it's not really interdisciplinary. In addition, it also … may get more marginal energy than core energy.
>
> What the Media Lab did that was unique was that it was an interdisciplinary center where people were based in the Media Laboratory, so that their primary affiliation was in the Media Laboratory, which meant that it was getting core energy and not marginal energy. I think that there's a lot to be said for that kind of structure.

2. Cohesion. Working together within a local institution for an extended period of time provides team members increased opportunities to learn about one another's strengths and weaknesses. Consequently, the team can perform efficiently and productively. Cohesion played an important role when the eight members of the R.E.D. group recently collaborated in the "*XFR:* Experiments in the Future of Reading" museum exhibition. A massive undertaking for a group of eight, *XFR* consisted of eleven exhibits revolving around the theme of reading in the future. Each exhibit was a complex amalgam of art, design, and engineering. The project proved appealing to outsiders: between March and September 2000, more than 350,000 people visited the *XFR* exhibit at the Tech Museum of Innovation in San Jose, California.[4] Two individual exhibits won the National Design

[4] See "2001 I.D. Interactive Media Design Review" in *ID-- International Design Magazine*. July, 2001. See also http://www.hum.uit.no/dok/ntbf/nr14.htm.

Award and the group has applied for eleven patents for the technological innovations created for the show.

Given the project's scope, it is not surprising to note that *XFR* almost failed to be completed on time. As the deadline for the initial unveiling approached, R.E.D. members worked frantically — literally day and night for weeks — to get the job done. Several subjects testified that the group's hurried work was successful, in large part, because of its cohesion. R.E.D. members had worked together long enough that by the time *XFR* was nearing completion, they were fully acquainted with each other's strengths and weaknesses. This familiarity existed on a topical level — for example, skilled at using lighting for artistic purposes, Dale MacDonald received all lighting jobs— but it also existed on a personal level. For instance, when working around the clock became a necessity, group members made adjustments for each other's working styles and external commitments. These adjustments led to the successful debut of *XFR* and helped build even greater cohesion within R.E.D..

3. Ability to tackle large, long-term projects. Another strength of local institutions, as viewed by the researchers we interviewed, is also illustrated by the R.E.D. group's work on XFR. Researchers affiliated with a local institution are better able to tackle large, long-term projects than those in virtual institutions are. Though individuals at virtual institutions can certainly work on complex projects, the construction of a piece like XFR or Media Lab Professor Tod Machover's Brain Opera (a multi-room, interactive exhibit first staged in New York City and now in the House of Music in Vienna) requires a commitment of time and manpower that is probably only available in institutions where people stay on particular projects for long periods of time.

Questions and concerns about local institutional affiliation

1. Risk of fewer new ideas. Visiting or virtual institutions have an advantage over local institutions when it comes to sheer production of novel ideas. When projects require diverse areas of expertise and innovative solutions, cross-pollination becomes particularly promising. For example, the Santa Fe Institute has only a few more residential faculty than the R.E.D. group has members, but each member of the SFI faculty has the opportunity to interact with over 100 visitors from a variety of disciplines each year. For institutions focused on innovation, this kind of difference is important. None of the people we interviewed wanted their respective institution to become rigid, and new faces mean fresh ideas. Because of this, in thinking about the organizational structure of a Center for Future Arts, emerging from the MIT Media Lab, Tod Machover told us that he would favor a strong fellowship program through which visiting scholars could build intellectual relationships and carry out projects.

2. Difficulty of finding specific types of individuals. Institutions built on local affiliation can sometimes develop organizational cultures that make it hard for them to assimilate “outsiders” easily. In the past, for example, the Media Lab showed a tendency to hire MIT students as faculty. Institutional leaders believed, in part, that people who were educated in and around the Media Lab would have a big advantage over individuals from other institutions when it came to carrying out research in the lab’s unusual environment. Media Lab leaders and individuals at other local institutions, like the Arts and Science Lab or R.E.D., must spend more time and energy picking new members than those at virtual institutions. Furthermore, these unique individuals may be difficult to find. New members who enter a local institution from the "outside" may feel uncomfortable, at least at first, in what may seem like a particularly insular environment — one that is only distantly linked to core disciplinary communities.

3. Demanding extreme flexibility. In order to stay fresh, interdisciplinary institutions often seek out new areas to investigate. This is certainly the case at the Media Lab. In fact, one of the lab's mottos is "We invent the future." As what constitutes "the future" has changed, so have the contours of the Media Lab's research. Faculty members who studied topics that could be broadly described as multimedia in the 1980's and who moved on to study "bits and atoms"— the embedding of electronic devices in everyday objects — in the 1990's, are now pursuing topics like affective computing.[5] Executing these shifts with a stable body of researchers, which is characteristic of a local institution, is a difficult task. The researchers must be intellectually flexible — often forcing themselves to work outside of comfort zones. At the Media Lab, the demand for flexibility is high. For example, founder Nicholas Negroponte often asks new faculty members upon their arrival at the lab to put down whatever they were working on and focus on something completely different. An episode that he described illustrates the degree of flexibility required.

> When Pattie Maes was hired, she had done some extraordinary six-legged walking machines and … some very fundamental work in the algorithms

[5] Descriptions of all the Media Lab's research projects can be obtained from the lab's Web pages, available at www.media.mit.edu

> to how six-leggedness works computationally. When she came, I said, "Forget legged motion. Use the next two months to think of other things." She was shocked. She said, "But you hired me for my world stature in legged motion." I said, "No, we hired you because of your intelligence and your ability to do these things." Most of the faculty who come are a little shocked by that, but then go off and do other things and try other things.

This practice stands in stark contrast to research experiences at more "typical" academic institutions, where faculty members are recruited with the expectation that they will continue to work in their areas of expertise. Negroponte pursues his unique strategy because he believes that individuals are likely to bring unusual and valuable insights to areas with which they are not particularly familiar. His strategy has worked well among the rare individuals working at the Media Lab — individuals who are willing and able, at a moment's notice, to drop their specialty and begin working on a different topic.

Virtual institutional affiliation

Positive attributes of virtual institutional affiliation

By hosting more people, institutions favoring virtual affiliation allow for rich cross-pollination of ideas and skills. In addition, the researchers we interviewed told us that as members of these institutions, they are often freed from stifling organizational constraints and are more flexible in their choice of new problems of study.

1. Freedom from organizational constraints. Though the environments in institutions with local affiliation are far from constricting, individuals at institutions with strong virtual affiliation (e.g., CIMIT and the Santa Fe Institute) claimed to enjoy an especially high degree of freedom. This freedom stems from individuals' abilities to carry out their interdisciplinary work outside the micro-culture and rituals of their primary professional homes. When working as visiting scholars or network members, the researchers we interviewed reported being free to pursue work that they find interesting without having to worry about how it will look to others within their home institution or whether it will fit into a particular organizational structure. One member of CIMIT's Operations Committee, Jonathan Rosen, spoke to this issue when describing the Committee's relationship with CIMIT's network of researchers. He told us:

> We're not a department. We're not involved, for the most part, in their promotions as academic clinicians or researchers. So we're not their bosses. We're not their chiefs or chairmen and so on. We have a strong support agenda.

2. Flexibility in the choice of new problems. Every interdisciplinary institution we investigated is committed to staying fresh. None of the researchers with whom we spoke wishes to revisit the same topic repeatedly, particularly if the topic is being thoroughly investigated elsewhere. Consequently, the foci of interdisciplinary institutions tend to change rather quickly, sometimes dramatically. An organization like the Santa Fe Institute can shift its focus simply by recruiting visitors in whichever disciplines the core members have an interest, provided that funding can be secured. In the 1990's, for example, SFI began to devote more of its energy to biological research than it had in the past and was able to attract scores of biologically-inclined researchers to its campus for stays of various lengths. Now SFI supports a large number of projects that deal with biology. It has undertaken an institutional change that would have been difficult to achieve at a local institution.

Among the institutions built on virtual affiliation, those with a more defined agenda (e.g., CIMIT) might not wish to make such dramatic changes. Even so, these institutions can probably tackle new topics within their general area of interest more easily than institutions with a smaller and more stable group of researchers.

Questions and concerns about virtual institutional affiliation

1. Good work may take some time. Many subjects told us that in order to do good, collaborative, interdisciplinary work, two researchers from different disciplines must develop a common language that allows them to understand each other and grow comfortable enough with each other so that they can reveal areas of ignorance. Each of these steps takes time.

At institutions with virtual affiliation, there is a chance that two collaborators may not be together long enough to accomplish both steps successfully. For example, though most people at SFI seemed happy with the amount of time visitors typically spend at the Institute, some suggested that longer stays might produce more fruitful collaborations. Some visitors, these subjects said, pass through too quickly for a useful collaboration to form. We heard less about this concern at CIMIT, but it should be noted that multiple commitments make it difficult for many physicians and engineers to spend more than one or two days a week on their CIMIT work. Conceivably, therefore, the type of lament we heard about time at SFI could surface at CIMIT as well.

2. Time for novelty vs. continuity in visiting institutions. Closely tied to the time required to do good interdisciplinary work is the challenge of balancing time for exchanges with visiting colleagues from other fields versus time dedicated to advance one's current research. SFI Associate Vice President Ginger Richardson called this the tension between "novelty and continuity" — commonly experienced by researchers at institutions with a flux of visiting scholars. As Richardson put it:

> Researchers who are here for an extended period of time want to work, want to get some papers out. They don't necessarily want to interact with every one of the 150 visitors whom we have moving through the Institute. So how do you structure meaningful exchange between the longer-term people and visitors?

3. Time for extra-organizational work. As a network-based organization, CIMIT appears to be a more diffuse organization than SFI. It focuses more heavily on relatively long-term collaborations between two or three researchers. However, it is not unusual to hear CIMIT members acknowledge the difficulty of getting researchers to participate in the enterprise. The problem does not stem from lack of interest; instead, it is a result of time constraints. The doctors who are interested in CIMIT tend to be very busy and are usually outstanding members of their departments. Frequently, their departmental superiors are reluctant to let them devote time to CIMIT. In the words of one of our CIMIT subjects:

> The doctors are simply too busy. They don't have the time to sit down and think or — even if they have the inclination, their chairman won't let them do it. In fact, I've seen that a couple of times: the chairman is short-staffed and [says], 'I can't afford — you'd be gone for a day' or 'What are you wasting your time on this stuff? Do something useful.

Consequently, the organization spends a great deal of effort trying to find ways to solve this problem. Reuben Mezrich, an M.D./Ph.D. and member of CIMIT's Operations Committee, told us:

> CIMIT helps and can help by giving up money, by saying to a chairman, 'Here are some funds to help free up this researcher's time. There is no financial risk for your department involved in his participation. We will develop something that will, in the long run, pay off.' That's a great help. But also just getting them — the chairman or whoever the leading characters are — enthusiastic about the process ends up being important.

For its part, the Santa Fe Institute has had some difficulty convincing senior scholars to come on extended visits: people are reluctant to leave their roots. Murray Gell-Mann told us:

> I've been fighting lately to have more emphasis on senior people — people who are at the height of their careers, usually at universities — to try to persuade them with whatever means we can manage to come for a year or half a year or two years. It's very hard. People have their research groups and their families; they have children in high school.

Patterns of institutional affiliation revisited

Each of the institutions we studied strikes a different balance between local and virtual types of affiliation among its members. These affiliations define patterns of access to human and technical resources. Affiliations are also associated to distinct patterns of interpersonal relationships underlying these institutions' cultures. Long-term local affiliation generates a strong relational tapestry that proves powerful when the relationships with particular clients or funders matter and when projects involve long-term commitments. It adds continuity and personal accountability to the dialogue that researchers establish with particular beneficiaries and supporters of their enterprises. Virtual affiliation, on the other hand, seems best fit to respond to changing audiences and funding requirements. Partial dedication allows researchers a safe haven to venture into risky projects without putting their careers at risk.

B. The nature of innovations: *Push* versus *pull*

The institutions we have studied varied in terms of the kinds of problems or innovations that they chose to study. James Muller, Chairman of CIMIT's Operations Committee and leader of CIMIT's Vulnerable Plaque program, described two distinct research emphases:

> There is some technology we're *pushing* because we think it will be good, like MEMS [micro-electro-mechanical systems] sensors, and then there are some problems like stroke and vulnerable plaque [where] we're *pulling* technology [italics added].

An organization's research program may be described as *pushing* when it explores new intellectual territory, creates new and meaningful challenges for itself, and most importantly, when it creates knowledge or invents technology for which there is no obvious or pressing need. For example, Xerox's R.E.D. group and the MIT Media Lab study the interactions between humans and tools with an eye on life in the future. Members of the R.E.D. group speak of "speculative design," creating objects for users who do not yet exist.

In contrast, organizations are being *pulled* when they work on problems that are already clearly defined. For example, CIMIT seeks to improve patient care by creating medical devices that will address shortfalls that currently exist in medicine. CIMIT is organized around eight scientific focus areas — endovascular device development, image guided therapy, minimally invasive surgery, simulation, stroke, tissue engineering, trauma and critical care, and vulnerable plaque detection and treatment[6] — which all reflect existing medical concerns.

Push innovations: Benefits and challenges

1. Freedom to engage in visionary projects. Unconstrained by the requirement of immediate applicability of results, researchers at the Media Lab and the R.E.D. group at Xerox PARC are free to engage in visionary projects relevant to a future audience. These researchers believe that their work has set the foundation for groundbreaking innovations such as the development of multimedia displays, electronic paper, and the convergence of the television, computing, and publishing industries

2. Relevance in question. Progressive vision does not come without costs: both R.E.D. and the Media Lab have been exposed to critiques associated with their forward-looking nature. Several individuals whom we interviewed at R.E.D. told us that Xerox PARC, their parent organization, frequently questions the need for the group. Traditionalists at PARC would like to see R.E.D.'s funding go toward labs that produce solutions for today's problems. In the words of one R.E.D. member:

> We talk about speculative design. In some ways it's sort of speculative marketing as well, just speculating on people of the future and building things for them and trying to educate the people of today. … From [the] management, [R.E.D.'s exhibit, XFR] was quite well received when it came to exist. There was more skepticism among the researchers; engineers and scientists are pretty skeptical about design. … I think it's interesting. I think it's our own lack of marketing that's [inaudible word] and people perceiving XFR as having built toys without thought and research behind it or around it. That's something we have to fix.

[6] Ibid.

Similarly, critics point to the Media Lab and ask, “Where are the products?” The Media Lab has a budget that tops $30 million per year, yet it has put forth very few fully developed products that have made commercial impact. R.E.D. and Media Lab members respond similarly to these critiques. Both groups point to the fact that their institutions are proactive and work to anticipate the future. Thus, neither R.E.D. nor the Media Lab should necessarily be developing products for use today. In fact, many at the Media Lab are proud of the fact that few of their inventions have become hit products. To them that indicates that the institution is well ahead of the technology/human-interaction curve. Media Lab and R.E.D. members do not seek to develop products for contemporary markets — they strive to develop objects and techniques that will change the way people think about and live with technology.

***Pull* innovations: Benefits and challenges**

1. Institutional and social support. In contrast to programs designed to create new or future needs, efforts that focus on solving more defined contemporary problems are more likely to enjoy institutional and social support. In its development as a sustainable organization, the Santa Fe Institute had to shift its original focus from purely *push* to a combined *push* and *pull* institution. Many of the researchers at SFI are pioneers who *push* new areas of study into existence. They ask new and unanticipated questions, then find novel answers to them. For instance, researchers working in the Computation in Physical and Biological Systems group are studying new forms of information processing to continue the advance of computing technology in 10 to 20 years. As part of this initiative, one group is investigating feedback and control in natural and artificial immune systems.[7] During SFI's earlier years the majority of its researchers worked on *push* programs of this kind.

In the mid-1990's, however, some observers criticized SFI, saying its goals were too grandiose and the practical value of its work unclear.[8] As we mentioned before, these kinds of questions are often asked of *push*-oriented institutions. While some of the criticism was soon dispelled, several members of SFI told us that the debate has had an impact on the Institute's agenda in the last several years. SFI began to emphasize more *pull* programs, and consequently, it now enjoys greater financial and social support. Doyne Farmer, McKinsey Research Professor at SFI, explained:

> The main part of the mission that's changed over time has been in the approach or the goals of what's being done. There was a period … ten years ago or more, where the focus was much more on big ideas — blue sky thinking. Then the pendulum swung back a few years ago to making things more grounded, pushing harder on being concrete and making models that actually explain specific things in the world.

2. Applicable products and enhanced visibility. An agenda that centers on contemporary problems allows an organization to produce devices that are likely to add to the organization's credibility. Among the organizations in our study, CIMIT is the most devoted to — and the most likely to garner credit for — the innovation of tangible, physical products for immediate public use. If CIMIT achieves lasting success, it will most likely be due to the products developed by CIMIT collaborators. An institution that seems to resemble CIMIT closely in this respect is the Media Lab. Indeed, everyone there

[7] Visit www.santafe.edu/sfi/research/indexResearchAreas.html

is committed to building things. The “demo” — a physical demonstration of an innovation — is the main form of output for Media Lab students and professors. However, most demos do not leave the Media Lab as finished products because the institution’s objective is not to design products but to produce ideas. Corporate sponsors pick up ideas from Media Lab demos and then build new devices themselves.

3. Maintaining a focused agenda. Among the organizations we studied, CIMIT was most clearly designed to address a pressing contemporary problem—the improvement of patient care. CIMIT’s emphasis on patient care informs the criteria used to select needed disciplinary areas of expertise. Disciplines that play a role in CIMIT research must directly inform the problem. The disciplines involved are therefore limited. Such focus stands in contrast to the situation at the Media Lab, where researchers are free to innovate in a limitless number of areas and draw on almost any discipline. CIMIT’s commitment to creating devices that will have an impact on current issues in medicine allows the organization to focus and maintain a clear agenda. For instance, some members of CIMIT reported that while there are many ways in which engineering and physics can contribute to the development of devices, CIMIT researchers’ efforts are guided by the fact that what they develop must be useful in specific medical situations. Consequently, CIMIT researchers often cannot, and do not wish to, follow through on a particular idea from engineering or physics to the same extent that someone at the Media Lab or the Santa Fe Institute might.

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[8] For a critical review of SFI, see Horgan, J. (1995). “From complexity to perplexity”. *Scientific American*, www.sciam.com/explorations/0695trends.html

Push and *pull* revisited

Like any categorical definition, concepts like *push* and *pull* describe ideal types of innovations. None of the institutions we studied represented a research orientation that was a pure case of one or the other. While each place represents a mix of both *push* and *pull*, the majority of institutions we studied are geared toward creating or at least anticipating an unprecedented future. At the same time, these institutions tend to draw criticism directed at the immediate, practical value of their efforts. The predominance of *push*-oriented institutions in our study may stem from the sampling criteria that guided our selection of organizations. We selected institutions with ample experience combining disciplines in novel, unprecedented ways (e.g., computing and art; mathematical modeling and history). It could be argued that this long-stretched combination of areas of expertise frees researcher's minds to become broad visionaries — individuals able to think broadly about knowledge and about their times. At the same time, the uncharted terrain in which they work poses challenges in collaborative interdisciplinary efforts.

C. Gathering expertise: Collaboration versus hybridization

In the interdisciplinary institutions that we studied, people's expertise is gathered in one of two forms. One form is collaboration between two or more individuals who are specialists in different disciplines. The other form is found in the work of people whom we have termed "hybrids," individuals who have mastered two or more disciplines. Predictably, the researchers we interviewed varied in how they carried out their work. Each institution presented a particular blend of collaborators and hybrid thinkers.

CIMIT, for example, proved to be overwhelmingly oriented toward collaboration. The majority of its researchers can be reasonably categorized as physicians or engineers, who are brought to work together. The organization as a whole is philosophically disposed to collaboration. Of course, hybrid individuals exist at CIMIT. For example, many members of the organization's Operations Committee have a great deal of experience in both medicine and engineering. However, the institutional tendency of this network of professionals is toward collaborations.

The Media Lab, on the other hand, leans toward hybridization. Though he was referring to the members of his research group, Hiroshi Ishii could have been speaking about the entire Media Lab faculty when he told us, "We are designers, artists, engineers, and scientists — we do all." Furthermore, several Media Lab professors told us that they train their students to become disciplinary hybrids. Media Lab faculty work with their students on interdisciplinary problems and do not tend to collaborate with other faculty on a regular basis.

Collaboration: Positive attributes

1. Informed problem definition. Some of the researchers we interviewed argued that in collaborative work, individuals benefit from each partner's familiarity with current questions and concerns in their respective fields and can steer the collaboration toward those issues. These researchers appear better equipped to identify interdisciplinary problems that are relevant to two or more domains of knowledge. In rapidly growing disciplines, it is likely that hybrid researchers will have difficulty staying up-to-date in both of their disciplines simply because of time constraints. Consequently, there is a chance that such individuals will make less-than-optimal connections between the two disciplines. These mistakes in connection-making need not be egregious: simply being unaware of recent developments can result in the repetition of work done elsewhere.

2. Efficient blending of disciplinary expertise. Once an appropriate problem has been selected, a new issue arises: how can one cover all the disciplines necessary to provide a solution? To explain why CIMIT has consistently chosen to cover its disciplinary bases via collaboration between engineers and physicians rather than with hybrid M.D./Ph.D.'s, interviewees cited efficiency. It is simply easier and less time-consuming to have an engineer work with a physician than it is to develop interdisciplinary hybrids. Reuben Mezrich's response to one of our questions about collaboration versus hybridization is roughly representative of what we heard throughout the organization:

> I think you need both people [a physician and an engineer] there because there aren't that many people who, in themselves, have enough a) knowledge of what the medical world is like and b) what the technical possibilities are. … There are a few, but not that many. … It's easier to find two people with the talents who, if you can get them to work together, can brainstorm and get the ideas flowing, take advantage of it. It's just easier. To get to be a good doctor, you've got to learn a lot and gain the experience because, again, there's no underlying theory. So the more disease you see, the more you get to understand disease. It sucks up time, and so you don't have the time to learn enough mathematics or enough engineering to be able to fashion a solution. That's why I think it's much more efficient, instead of trying to grow one, to put them together.

Collaboration: Questions and concerns

1. Egotism and cross-disciplinary condescension. One obstacle that arises when individuals collaborate is unsurprising: individuals from different disciplines often are condescending to one another. Over and over again, subjects at institutions which rely heavily on collaboration cited individuals' egos as a barrier to joint work. CIMIT's Reuben Mezrich speaks of the difficulties associated with collaborations between physicians and engineers:

> One of the problems that has to be overcome, and I'm conscious of trying to overcome it, is a lot of the doctors here have a problem and say, 'Ah, this guy [an engineer] can fix it for me.' The problem is … the doctor treats an engineer as a technician. 'I got this little problem, make me this gadget, thank you very much, good-bye.' No collaboration.

If two researchers are to work well together, egos must be put aside and each person's unique capabilities respected and utilized. If these actions are not taken, a collaboration will not be as effective as it could be, if it is effective at all.

2. Lack of a common language. Researchers from different disciplines who can shelve their egos are quickly faced with a second problem: they must find a way to get past their specialized languages. Each discipline has its own jargon, designed for any number of reasons. Interviewees referred to specialized disciplinary languages as making intra-disciplinary communication more efficient and as a tool to exclude outsiders in a particular field. In the words of one of CIMIT's collaborators:

> If you put a molecular biologist in a room with a surgeon, and the molecular biologist has codified the language of genes with fluc1, zif2, hedgehog3, and we're doing the promoter on the Z deal of the blah, blah, blah, you can't understand a word they're saying. Zero. And if we're talking about the anatomic dissection of the retro peritoneal plane, dissecting out the arcuet ligament — it's efficient within specialties, but it's a complete show-stopper between specialties. It serves two purposes. One purpose is it's efficient language for a specialty. The

> other is, if I say something that you don't understand, it means I'm smarter than you are. So both of those things are problems.

In order to find those areas of overlap, this researcher instructs his lab members to converse about their problems as though they were speaking with fifth graders.

> What I've tried to do is, if you're putting groups together, one, they have to have mutual respect for what each is bringing to the whole. There has to be respect. Two, you have to get rid of the language. So what we do is, we say every discussion has to be as though you're talking to a fifth grader because most of the concepts are not that hard. In any field you can sort of get it if it's explained to you. So it has to be explained properly. The way to do that is a common language. That's about the fifth grade. That's what we do.

If an individual is unwilling to attempt to speak in this manner, this leading researcher will simply not allow him to remain in the lab. Individuals at other institutions, particularly SFI, have told us that they use tools that cut across disciplines — non-linear mathematics, for example — to create models, which they use to translate between disciplines. We will come back to the role and nature of common languages later in this paper where we explore the phenomenon from a cognitive perspective.

3. Different intellectual tools. Collaborations are formed because researchers believe that their backgrounds and skills, though different, are complementary. Sometimes however, the differences end up outweighing the similarities. Occasionally two researchers can arrive at a common language and still have difficulty working together because of drastic differences in their mental toolkits. For example, in referring to his work at two interdisciplinary institutions, the Santa Fe Institute and the Arts and Science Lab, James Crutchfield told us about the challenges he faced when working with biologists. Having found biologists amenable to his theoretical approach and with a common language worked out, Crutchfield has sometimes run into trouble because the mathematical tools with which he works have alienated his collaborators.

> You have to be very careful, especially if you're in physics or math, when you talk to people in other disciplines to work on one of their problems because many of them had — I speculate here, but … it is a summary of my interactions — bad experiences with mathematics, and they feel intimidated by it. So you can even imagine a very positive situation where you're the experimentalist, I am the theorist. I've got some idea we can actually start talking about. It looks like there's some real resonance. Then I go to the board and start writing down my [mathematical] theory, it is like I just left you behind … .

This sort of problem can derail a collaboration. Crutchfield told us about two ways in which he deals with this situation: he either teaches his collaborators mathematics, or he does not describe all the mathematical details to his partners. He just tells the experimentalist what is relevant in their experiments. "Forget the cool thing you found about solving this equation. Big deal." Of these two solutions, the first is clearly preferable. However, it can also take a great deal of time as well as a willingness to learn on the part of Crutchfield's collaborators. The second method is less taxing, but it means that the biologist may be left unappraised of certain important details in the collaboration.

Hybridization: Positive attributes

1. No need to find a common language. Hybrid researchers have certain advantages over pairs of specialists when facing the challenges of interdisciplinary work. Rather than laboriously seeking a common vocabulary to communicate effectively and work productively with other experts, hybrids can mentally translate back and forth between different disciplines.

For example, Media Lab professor Mitch Resnick, who specializes in the educational use of technology, probably has an advantage over educators who collaborate with computer scientists to produce educational tools. Resnick understands his problem space well and is neither intimidated nor confused by either discipline's jargon. Resnick does not need to spend time trying to figure out what his collaborators' technical terms mean, and he does not need to waste energy trying to hide ignorance, as some collaborators might be inclined to do.

2. Deep integration made more plausible. In addition to having specialized languages, each discipline also has its own set of goals, methodologies, and history. All of these can be barriers to cross-disciplinary communication. Many organizations have decided to surmount these barriers by having people from the different disciplines work together. As detailed above, sometimes this works well. However, a counter-argument to the benefits of collaboration can also be made: a hybrid who understands the intricacies of two complex disciplines will sometimes have an easier time forging a meaningful synthesis than a pair of specialists will.

For example, consider the work of Media Lab professor, Tod Machover. Machover's Brain Opera, "an interactive, musical journey into your mind . . . presented simultaneously in physical and cyberspace,"[9] integrates music and computer science seamlessly. A description of one of the Brain Opera's three main components, the Mind Forest, hints at the complex interplay between the disciplines involved:

[9] http://brainop.media.mit.edu/onsite/main.html

> The Mind Forest is a complex space filled with hands-on experiences that turn body gesture and voice input into music and images [Tod Machover and Sharon Daniel's fields respectively]. The space was designed by architect Ray Kinoshita, and is intended to create the impression of walking, figuratively, into a giant musical brain. Organic shapes and materials designed by Maggie Orth, and responsive, invisible sensors invented by Joe Paradiso and his team, help make the environment feel natural and responsive rather than high-tech and mechanical.

The Brain Opera and other similar projects illustrate how Machover reaches deep integration of specialties in two or more disciplines. Machover is so immersed in music and technology, and has been for so long, that he can pinpoint promising areas of disciplinary overlap and explore them gracefully.

Machover's understanding of music and computer science allows him a privileged view of the creative problems he examines — one that composers and computer scientists working together may struggle to reach. In the late 1970's and early 1980's, while still in his 20's, Machover was an important figure at IRCAM, the Institut de Recherche et Coordination Acoustique/Musique. IRCAM was spearheaded by Pierre Boulez; its mission was, and still is, to explore and produce electronic music. When Machover was there, groups of musicians and scientists worked separately, meeting from time to time to discuss their work as they moved toward common goals. During our interviews he described one of these meetings which illustrates the challenges of cross-disciplinary communication, even when the groups have shared aims:

> Stockhausen came with his list … . He wanted to have something that would allow you to play the trumpet, and have the trumpet sound turn into a voice, and turn into this and that very beautifully … but nobody knew how to do it, and they kept telling him. And he kept saying, 'This is what I want. I don't want something else … . Then the scientific director came in. He said, 'Okay, we've talked about this. I thought of your [Stockhausen's] requests. The first three things on your list, if we can solve them, the

> person could get a Ph.D. like that from Stanford or MIT. The second five things on your list, Nobel Prize. The last 15 things on your list violate all the known laws of physics.

Hybridization: Questions and concerns

1. The risk of superficial coverage. Researchers in both camps, hybrids and collaborators, referred to the risk of superficiality as an important challenge faced by hybrids. David Dunn personalized the challenge as he addressed the difficulty an individual has in staying on top of developments and raising new questions in more than one discipline:

> I think you pay a price for being the kind of generalist that I strive to be. The first price I think one pays is a loss of credibility in terms of people who are really involved, and rightly so, in their particular disciplines. As I start jabbering away in terms of references to cognitive science or complexity theory or mathematics or whatever, people who really live in those worlds, for the most part, are not going to take me seriously. They probably shouldn't because I'm obviously an amateur dealing with those things. And I don't care because … what's important is that I can create this kind of cross-disciplinary and cross-enrichment between these things to create some other kind of meta-pattern.

2. The challenges of developing good hybrids. Some of our interviewees explained that it takes a great deal of time and energy for an individual to become a hybrid, and that time and energy might be more efficiently and effectively used in another manner. CIMIT researchers, for example, favor collaboration between experts because of the graveness of the organization's work. Medical products developed on the basis of CIMIT research could mean the difference between life and death. Generally speaking, the organization fears that hybrid researchers might be stretched too thin to understand and handle all of the issues that must be addressed during the development of medical devices. Furthermore, they fear that developing this interdisciplinary expertise might simply take too long.

Collaboration and hybridization revisited

By definition, interdisciplinary work takes place in the hybrid terrain where two or more disciplines overlap. All the researchers whom we interviewed value a fair representation of the particular disciplines involved in their projects. They value experts' sense of the relevance of particular problems in specific fields; they value the methods and modes of thinking embodied in these disciplines. Honoring the particular bodies of knowledge matters to these researchers. The test of an innovation and the peer review of a publication often operate along disciplinary lines and are central to the success of a particular product or idea.

The institutions we visited vary in the degree to which they prefer to have two or more areas of expertise embodied in a creative collaboration or in a single person. Both collaboration and hybridization offer particular benefits in the eyes of our interviewees. Preference of one method over the other seems to depend on several factors, including the personnel available, the scope of the disciplines involved, the gravity of the work the institution does, and the complexity embedded in the particular bodies of knowledge exchanged across disciplines.

IV. Interdisciplinary Workers

In the process of determining the institutional characteristics that support interdisciplinary work, we identified a set of individual dispositions, epistemological strategies, and cognitive skills that prevailed among our subjects regardless of their institutional affiliations. In this section we focus on individual qualities that our subjects associated with interdisciplinary workers. We begin by addressing a set of four *dispositions*: broad-ranged curiosity, open-mindedness, risk-taking, and humility. We propose three *epistemological strategies* that individuals used to organize and integrate knowledge and skills gleaned from multiple disciplines: fluid thinking, translation, and explicit integration. Finally, we identify three *cognitive skills* that play a central role in subjects' interdisciplinary initiatives: analogical thinking, developing a common language, and holding a metadisciplinary view.

A. Dispositions

Interdisciplinary workers seemed to display certain personality traits or dispositions that attracted them to ventures that cut across disciplinary boundaries and made them valued members of interdisciplinary projects. They exhibited a particular sensitivity for ideas and modes of thinking embedded in multiple disciplines. They showed an ability to use a broad-ranged knowledge base effectively in embracing risky research projects. Furthermore, their life stories revealed an inclination to intertwine bodies of knowledge recurrently over time. Four of the most prominent dispositions that our study revealed could be described as *broad curiosity*, a *willingness to embrace risk*, *disciplinary-rooted open-mindedness*, and *humility*.

1. Broad curiosity. Curiosity in multiple areas of knowledge was a mobilizing force for the interdisciplinary workers in our study. Curiosity emerged implicitly in their accounts of professional growth as well as explicitly as a driving force of interdisciplinary work.

Consider for example Woody Vasulka, the artistic director of the Arts and Science Lab. He was originally trained as a metal worker in Czechoslovakia, then pursued film as a student in the 1960’s, and through his New York film contacts, he discovered the new and “uncontaminated” medium of video in 1969. He and his wife, Steina (originally a classical violinist and now co-artistic director with him), immediately began to apply audio tape techniques to video making and editing. From work in analog video and sound, they ventured together into computer programming and network environments, learning each new technology as soon as it emerged. Vasulka conceives of his art as projects or “studies” in how things work. He creates less from a feeling of divine inspiration than from a curiosity about phenomenology. For instance, his computer work grew out of a fascination with code and a personal need to know exactly how computers worked. In his attempt to analyze the state of transformation between the real and the virtual, or the process of change from analog to digital, he has undertaken several technological and artistic studies.

The Vasulkas’ colleague and Art and Science Lab Director, David Dunn, is a sound artist who has done pioneering research in the field of bioacoustics. His work with a University of Michigan biologist, which documented a rare instance of insect language, originated in his exploration using underwater microphones and recording the sound in a vernal pool — an excursion he made "just out of curiosity." Dunn believes that curiosity is one factor without which interdisciplinary work could not take place. "Anybody who does this kind of thing … has to be driven with just a kind of innate curiosity about the nature of the world."

Other scientists at SFI shared Dunn's view. External faculty member Ricard Solé credits his colleagues with "tremendous curiosity." Though scientists "are curious almost by definition," they can also be curious "and very narrow." That is not the case at SFI, where Solé finds peers who are commonly interested in philosophical questions to a degree and a depth that amaze him. Doyne Farmer, leader of the Complex Systems Group at SFI, lists curiosity as the first characteristic that marks individuals pursuing ideas across disciplines. "I think one of the things that drives … interdisciplinary work is feeling like there's a huge body of knowledge out there, and … just not [being] satisfied settling into one niche and ignoring the rest." Mark Newman goes so far as to describe the scientists at SFI as "intellectual omnivores." John Parrish, director of CIMIT, also lists curiosity as one of the defining characteristics of the individuals who make up his organization's leadership. He describes its members as individuals who really want to figure out and understand particular problems so that they can solve them. Ronald Newbower, Chairman of Strategic Planning for CIMIT, adds that one needs to be curious and open-minded "almost to the point of attention-deficit disorder."

2. Disciplinary-rooted open-mindedness. Open-mindedness is the second trait repeatedly attributed to interdisciplinary workers and collaborators. Newbower includes it, along with interest in a wide variety of things and an eagerness to grab ideas from wherever they might occur, as characteristic interdisciplinary dispositions. Newbower states that open-mindedness is most often the result of feeling secure in one's own discipline; it is the counterbalance to knowing the discipline well. The confidence one gains from accomplishment in a discipline helps to feed intellectual exploration rather than to hinder it.

Dunn detects disciplinary confidence in James Crutchfield, the scientific director working with him at the Arts and Science Lab . This trait enables Crutchfield to branch out of narrow scientific circles. Dunn comments:

> Jim is unique … . First of all, he's not insecure. He's not at all insecure as a scientist. So he has less fear about hanging out with artists. One of the things I've noticed is people in certain scientific disciplines, there's a sense that they will be thought of as less rigorous or under suspicion for contributing in certain ways to this kind of an organization. From the scientific side, it takes someone who is both open, flexible, and very secure within his or her own discipline.

Anne Balsamo, a research scientist at Xerox PARC, describes the open-mindedness in her R.E.D. group colleagues as an "intellectual generosity" which includes deep respect for "the intellectual sensibilities of the other people." While regard for another's ideas does not necessarily entail agreement, a base level of respect is "absolutely necessary" for their interdisciplinary collaboration. Like Newbower and Dunn, Balsamo traces the generosity to security:

> … how are you intellectually generous? You're intellectually generous when you yourself feel secure in what you know, and the insights and the wisdom and the knowledge and the creativity that you embody. It's important to be secure, [knowing] that you do have value and something to offer.

She adds that security stems from being comfortable with the fact that one doesn't and cannot know everything, and is ideally accompanied by the realization that one has "some really exciting things to learn from the other people."

Balsamo's colleague, Scott Minneman, thinks of open-mindedness as "just being able to kind of appreciate or be interested in other perspectives." Having worked with interdisciplinary collaborators who weren't "willing to budge very much" from their own opinions, Minneman thinks that a "really natural curiosity about other people's perspectives [and] valuing those highly is a really important thing." He describes it as:

> Working really, really hard to try and get our heads around what it is that these other people are bringing to the table at any particular moment. I think that produces a lot of good will within the group because you do feel like you're being heard, and decisions are being made, and choices are being made, with a good basis behind them.[10]

3. Willingness to embrace risks. To engage in interdisciplinary study or work, one not only has to be confident enough within a discipline to explore outside of it, one also needs to be willing to participate in areas that are often unexplored and difficult. Interdisciplinary projects are often time consuming. Since validation standards are often ambiguous, areas of intersection are ill-defined, and areas of expertise are multiple,

[10] A corollary of disciplinary security is disciplinary success and accomplishment: the achievement of professional security, be it tenure or national reputation, affords the researchers we interviewed the luxury of more non-traditional choices than would be available to a beginning or mid-level practitioner. According to Newbower, several of the CIMIT collaborators "are senior, established full professors; they've done

interdisciplinary projects are sometimes also prone to failure. In a professional and academic world that is largely defined by disciplines, an interdisciplinary worker or collaborator must take on a degree of risk. According to Jonathan Rosen, Director of CIMIT's Office of Technology Development:

> There's a real risk … from a career development side. The organizational structures that we work in - in individual institutions - reward individual contributions still today, almost exclusively…. So the ideal CIMIT investigator might be one that has the hardest time advancing their own career. So that, to me, is the downside of this concept. The system doesn't reward interdisciplinary commitment as much as it rewards individual advancement.… The more interested you are in things that happen between fields, the less you're associated with expertise in any particular field. So there are personal choices associated with that as well.

Occasionally, interdisciplinary risk takers find themselves shifting careers when their original training was well underway and successful. For instance, Ronald Newbower entered a post-doctoral program in medicine after earning his Ph.D. in physics. He refers to the risk he took "by not following the prescribed pathway for Ph.D.'s coming out of institutions like Harvard in a field like physics — to go down the straight and narrow … . [Colleagues] almost wrote you off as obviously demented."

At times interdisciplinary risk-taking means committing to apparently unsolvable problems. Reuben Mezrich, Director of Technology at CIMIT, contrasted the fearlessness of MIT graduate students in his Medical Innovations class with the conservative disposition of established Ph.D.'s. in a study group at the National Science Foundation. A reviewing researcher refused to approve five years of support for the design of a particular medical device because it "was too difficult" and "would never work." This

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what they've wanted to do … They've reached a point where they want to play more of a mentoring same device was built and tested by a daring students within two months. Ricard Solé notices the same courage in the post-doctoral fellows with whom he works at the Santa Fe Institute. They are willing to court a high rate of failure in an area that has never been investigated at the risk of not only failing to find an answer, but also failing to follow the traditional academic road to tenure.

> Here [at the Santa Fe Institute], there are people, like post-docs, who are trying to solve problems that in other places will be considered a kind of suicide. In terms of really huge problems — it's trying solve these in three or four years. Whereas in other places, a post-doc usually is supposed to be someone who's going to be making something original but inside something that is already going on. Here, some of the post-docs are … considering to solve really deep problems that nobody has solved. … It's risky.

One of CIMIT's researchers credits his involvement in CIMIT to the organization's allowing him to take on cutting-edge scientific projects that he would not be able to engage in otherwise. CIMIT offers a framework within which to do "risky" interdisciplinary work. It provides researchers and their home departments with the funds needed to do unconventional and path-breaking research. As he puts it:

> [One of CIMIT's most important contributions stems from] the ability to actually direct resources to these projects that would just not be funded in any other way because they're, at this point, so high risk. So the ability to actually have discretionary monies to throw into a very high-risk undertaking is important.

4. Humility. The desire for professional recognition and success can breed intense competition in fields like medicine and science, as well as in the highly publicized world of art. The struggle for and achievement of success can foster egotism and territoriality. According to Ellen Goldberg, Director of the Santa Fe Institute, it can even lead to

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role….they don't have that promotion pressure."

interpersonal conflict when renowned figures are unwilling to admit a theory or perspective other than their own. It is the lack of these traits and the presence of humility that characterize interdisciplinary workers of the institutions we interviewed in our study.

Humility is the most consistently mentioned quality by members of CIMIT's Operations Committee. People have to "check one's ego at the door," says Newbower, and get "to the point where they are comfortable asking a stupid question, which is absolutely essential to innovating in multidisciplinary areas. They have to be able to ask 'Why can't I do that?' or 'Explain that to me' or 'I don't understand what you meant.'" To get to that level of trust and comfort, he says, it takes time and the willingness to know that "you don't have to impress the cardiac surgeon that you're the most brilliant electrical engineer in the world" and vice versa. Newbower says that CIMIT spends a lot of time just finding people who have the "personality characteristics" to do that. He also says that people also select themselves: "The people who have the personality, who want to do this, are so frustrated by their inability to find willing partners in the process, that they are drawn toward the platform of CIMIT."

One CIMIT researcher similarly reports that when physicians and researchers from different sub-disciplines compete with one another or lab members try to prove that they are smarter than their colleagues, the team's work suffers. Interdisciplinary collaborators thus have to put "their egos aside." Rosen spoke eloquently about the same quality:

> The overwhelmingly consistent feature that I can see … is a willingness to allow others to win, to promote the others on the team over yourself. It's a humility. The greatest researchers we work with are the most human beings and the least interested in promoting themselves. They're willing to

> promote the people that work for them, that work with them, that help them. … It is partly a humility; it is partly a genuine sense on their own part that they're trying to help other people be successful. They are successful themselves, also, as a result.

In addition, Rosen tied humility, like open-mindedness, back to a fundamental sense of confidence in one's self and work:

> The definition … of self-esteem is not self-aggrandizement; it's the opposite. You have so much confidence in yourself [that] you're willing to take responsibility for mistakes instead of blaming other people. You're willing to reward other people over yourself because you are just so clear on who you are and why you're there and what you're trying to accomplish that you're generous as a result of that. You go through the ego thing and come out the other side with a sense of self-esteem and a clearness about your own personal mission that allows you to give things away. If you don't have that, you're not aware of your surroundings, let alone collaborative in your approach. [11]

According to Dunn, a similar quality marks the Arts and Science Lab community, which includes the four founding members, regular visitors, and annual conference participants:

> None of us really cares about being first in terms of something, as if we're running a race. We're really more just interested in being participants in this particular cultural environment and realize that there's a … co-evolutionary mutuality. Sometimes we're the ones who can push others, sometimes we make the innovation, sometimes other people do. But by creating this kind of environment where those things can be shared and by realizing that there really isn't a competition at work, ultimately … the agenda is … an evolutionary progression and being able to contribute to that.

Dispositions revisited

Without curiosity and the willingness to take risks, individuals are less likely to take on the challenges presented by interdisciplinary work; without open-mindedness and

[11] Newbower echoes the same conviction: "The secret sauce is this mixture of people who … love pulling groups together, who don't let their own egos get away, who are very secure."

humility, they are less likely to succeed in the interdisciplinary work and collaborations they begin. It could be argued that these dispositions are evidenced among individuals outside the institutions we researched and people who pursue disciplinary careers. Yet, when played out in an interdisciplinary territory, these dispositions reveal particular qualities.

Broad curiosity is not just a general interest in a collection of issues; rather, it is a tendency to explore various disciplinary perspectives and engage with them in-depth. *Willingness to take risks* assumes that the risk involves working in uncharted terrain that, unlike their comparable disciplinary counterparts, is defined by ambiguity, ill-formed assessment criteria, and lack of precedence. *Disciplinary-rooted open-mindedness* is not simply a generic disposition to listen to and empathize with others. When played out in interdisciplinary collaborations, it requires understanding somebody else's knowledge base and epistemologies. *Humility*, for its part, involves not only awareness of one's limits in understanding problems, but also a healthy skepticism regarding the very disciplinary perspective that one brings to the analysis of a problem.

B. Three *epistemological strategies* in interdisciplinary work

What is it like for interdisciplinary thinkers to cross disciplinary boundaries? Epistemologically speaking, how do they conceptualize the territory that lies at the crossroads of disciplinary lines of inquiry? How do they connect, integrate, and organize ideas and modes of thinking across disciplines? In our interviews, we sought to explore the ways in which two or more disciplines were intertwined in subjects' minds as they engaged in interdisciplinary work and collaborations. Each person was asked to identify the disciplines he or she used, explain how each of the respective disciplines contributed to the work, and describe how the disciplines became fluid, blended, or pulled in different directions in the process. The answers we received suggest three primary *epistemological strategies* among the subjects we interviewed. We term them (1) fluid integration, (2) translation, and (3) explicit integration. These modes of thinking represent overall epistemological frames through which individual researchers approached interdisciplinary work.

1. Fluid integration

Several of our subjects described the process by which they draw on and apply their disciplinary knowledge as “fluid.” SFI’s Ricard Solé defines his use of biology and physics in terms of a flow. He explains that it is not difficult for him to see “ideas or metaphors or universal genetic properties” that are very well known in physics applied in biology. When asked if he has ever had difficulty combining the two disciplines or felt pulled in different directions by them, he answers negatively while acknowledging that his ability to do so is “a very special case.” For many other people, he says, “If you are trained as [a] biologist and [a] physicist, this is not a big deal.”

David Dunn, and Woody and Steina Vasulka of the Arts and Science Lab describe their creative process as a fluid phenomenon in which they often do not distinguish between the different disciplines they use. Dunn says

> When I’m thinking about these things in a creative fashion, I’m not making distinctions most of the time. … I’m constantly just thinking about

> a larger range of ideas … an ecology of ideas where these things are all moving in and out of each other in very complex, and often eccentric, ways. That just happens to be the way my brain is made. While I'm capable of sort of settling it into categories most of the time, I don't. It's just a kind of fluidity that occurs.

In the process of his work, Woody Vasulka does not distinguish between his computer programming, his video work, or engineering. He describes the process as akin to "automatic writing," in which the pages of text that one has written cease to bear the mark of the author and take on a voice of their own. Steina Vasulka describes her creative process as a continual internal dialogue through which she compares what she creates — whether by programming computers, editing video, or manipulating electronic images — to the original image in her mind's eye. Part of that dialogue involves the technology itself, the machines she uses as "the means " to her artistic end. "Okay, so you can't give me that, but can you give me this?" she asks her computer. The next step is borrowing and stealing "from everybody and nobody," drawing on sources as diverse as classical artists to scientific journals. In the process, which she describes as being without clear disciplinary distinctions "in that soup," she intuitively knows what works and what doesn't.

It could be argued that fluid thinking operates best when the domains involved hold a "family resemblance"(e.g., biology and physics as part of the natural sciences) or when the creative challenge maintains a focus on the product itself (e.g., an exhibit, a piece of art). By sharing a preference for explanatory power, empirical grounding, experimental base, and parsimony, accounts of the natural world built through the tools of physics or biology may invite scientists to construct seamless integration. In contrast, with respect to cases in which the qualities of knowledge are clearly distinct, fluid thinking and seamless integration may take place when researchers focus on the quality of the products that they develop. For example, Steina Vasulka merges computer coding and its unequivocal logic with artistic expression, which thrives on ambiguity and fluidity. She focuses her attention on the qualities that she expects to see in her final product, which is ruled by the principles of new media art and guided by "the image in her mind."

2. Translation

Several of the researchers whom we interviewed described their interdisciplinary work as a translation between two disciplines. For instance, James Crutchfield and Mark Newman both described their interdisciplinary work as translating a secondary discipline into mathematics, the tool underlying their home discipline of physics. In Crutchfield's words:

> Since I enjoy using mathematics and I enjoy thinking abstractly … it's easy for me to look at other fields using the kinds of mathematical thinking I've been trained into. At times I feel lucky that the kinds of mathematics I learned as an undergraduate and graduate student at UC Santa Cruz, statistical physics … [and] dynamical systems theory, is so powerful. I feel like I'm cheating. They give a perspective that makes it easy for me to look at problems, say, in population genetics and re-represent them in my own language, which is this language of dynamics and mathematics.

Newman's experience is similar:

> I still do work in conventional physics and I am perfectly well aware when I'm doing that. … But when I'm working on these more interdisciplinary things then I don't think I have different modes. … [T]he way I work is basically quite mathematical, using physics techniques all the time, but applied to problems in other areas. That's pretty much the way it is. That's the way I make it.

Claims of this kind were not uncommon among members of the Santa Fe Institute and the Arts and Science Lab. Their work involves using sophisticated mathematical or computer-generated models to find patterns in biological, physical, social, artistic, or economic phenomena. Oftentimes, using mathematical and computing models allowed researchers to bridge disciplines that stand as epistemologically apart as chemistry and history. For instance, John Padgett , a political and social scientist from the University of Chicago, has been studying the history of Renaissance Florence in collaboration with theoretical biologists at the Santa Fe Institute. Models that are central to theoretical chemistry offered him a way to frame complex historical phenomena.

Padgett discovered the power of these models for his own work on the intellectual, political, and economic factors at play in 16th century Italy through a workshop offered at SFI by Michael Cohen. As a participant, Padgett was paired with another scholar and chemist, Walter Fontana. Each was told to present the other's paper. In doing so, they both realized that, once formally presented, Padgett's analysis of the Renaissance's sudden flowering in Florence resembled the abrupt physical transitions of chemical reactions and the birth of self-maintaining and reproducing cells.

> This got the two of us to notice that, at the very least, there was some interesting, at least analogs or strong analogs, between dynamic networks. He was interested in dynamic chemical networks; I'm very interested in historical social networks. If you put visual pictures up on the board of his chemical networks and my social networks … you'd be amazed how much similarity there is in just [their] architecture. … He was showing pictures of artificial chemical data and how they changed over time, and I was showing pictures of actual historical Florentine networks and how they changed over time. The fact that we presented each other's papers got us to focus in on that parallelism.

Since then, Padgett has researched and conceptualized his work in the scientific terms of autocatalytic networks.[12] He has recently finished a formal model of hypercycles in economic systems. Padgett runs a summer workshop that explores the simultaneous evolution of states and markets and is attended by biologists and social scientists alike.

A translation-based epistemological strategy centered on mathematical and computer modeling seemed particularly prominent among our SFI interviewees. This is not surprising given the very mission of the institution in which they work: to advance understanding of complexity and chaos theory as a tool to understand the world. However, researchers beyond this circle referred to *translation* as well. Marc Chow of the R.E.D. group, for instance, described this process of translation into a bridging discipline as “leading with your strongest hand.”

> In my case, it’s probably the filmmaking/video/storytelling hand. A lot of times, you use that as the hammer to pound the nails of the other problems that … come up in the other disciplines. So sometimes that works, describing an engineering problem in a very visual way, for example, or using the notion of telling a story.

In the cases of *translation* that we observed, the disciplines selected to operate as links were characterized by their formal quality: mathematics, computer modeling, and design. Knowledge in these disciplines must satisfy syntactic standards of coherence, internal consistency, and clarity among others. Mathematics, computer modeling, and design are formal languages that can be applied to describe phenomena in variety of empirical disciplines. These

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

disciplines were most widely used among interdisciplinary workers whose modes of thinking predominantly involved translation.

3. Explicit Integration

The third way in which subjects described their interdisciplinary thinking was in terms of *explicit integration* — a conscious combination of multiple disciplinary viewpoints into a coherent whole. John Padgett experiences the process in precisely the way that Solé, Dunn and the Vasulkas avoided:

> It is … [a] self-conscious exercise of taking on hats, putting off, on, taking a hat on, putting on another hat, looking at the other point of view from this perspective, and making myself self-consciously move around and have these multiple perspectives. So hardly a flow — much more of a schizophrenia.

He adds that he is exceedingly aware of the disciplinary roots of the tools or perspectives he picks up: the Latin he reads and the autocatalytic network paradigm in which he conceptualizes problems are "radically distinct."

The majority of R.E.D. members used to integrate separate disciplines that require distinct modes of thought as well. They reported that the disciplines have such varying ways of thinking that they can't be engaged in the different disciplines simultaneously. Like Padgett, Maribeth Back used to find that the disciplines were easy to differentiate because each had a "different mindset." In terms of navigating between them, she reported that it is difficult for her to work in certain disciplinary combinations on the same day:

> It’s not that hard to distinguish between them because they require different habits of thought. … I really find it difficult to operate as a creative designer on the same day that I’m doing programming. It’s just a different kind of thinking, and it’s very different also from trying to do reflective writing. … It’s not just programming; it’s also building, like soldering things together and doing actual physical stuff with the hands. Physical stuff with the hands and computer programming get into the same category for me. It’s prototyping: you are building something in each case. But it’s a different thing than doing conceptual design, and that’s a different thing than doing reflection and ideology.

Back’s friend, Matt Gorbet used to work in electrical engineering, mechatronics, computer programming, and graphic art.[13] Like his former R.E.D. colleagues, he acknowledged differences across the disciplinary modes in which he worked but saw them as opportunities for balance rather than tension. Gorbet preferred to work in all areas throughout the day rather than in one area in isolation. He enjoyed switching quickly back and forth between the disciplines while applying his insights. Only when time constraints forced him to be creative at a particular time in order to meet a deadline, did he feel tension between the disciplines he used. Like Chow and Back, Gorbet often gained insight into one discipline while working on another.

A common pattern across these experts’ descriptions of interdisciplinary thinking was their awareness of the territory in which they are working. Back, for instance, described the process as follows:

> I’ll be working over here and doing the engineering stuff and I’ll find some little thing that makes no difference to me, because I’m wearing my engineer hat, but then on the next day that I’m being a designer, I remember that and go, ‘Oh, that means—’, so there come these incremental breakthroughs though that cycle.

Similarly, Marc Chow, described the creative process

> You get these breakthroughs in spurts. A lot of times, because you mull over something in one discipline while another discipline is spinning around … issues are circulating around in the background while you're thinking about an engineering issue, for example. Then suddenly something comes along to reconcile the two. I think that's how — it's sort of the hitches and bursts of progress as opposed to very steady kind of progress.

Overall, several of the researchers we interviewed attempted to relate disparate disciplines through explicit integration. Some viewed the modes of thinking embodied in individual disciplines as being so disparate that they were unable to think in both disciplines at once. Others thrived with agile shifts across disciplinary perspective that inspired novel insights into the problem at hand.

A common feature in descriptions of explicit integration was researcher's reference to the nature of the disciplines involved. These researchers tended to address the challenges, opportunities, and constraints embodied in their particular disciplinary hats. They also seemed aware of the ways in which these constraints played out as they moved from hat to hat. Illustrating this bird's-eye view, Maribeth Back described the interaction of certain qualities of the various disciplines with which she works:

> Because I know what the engineering constraints are, to a certain degree, I'm willing to push [them] … because I have … some idea of how long it takes to build something. … If I didn't know about that from an engineering standpoint, I might go over here in the design world and make something completely irresponsible. And if I'm making something completely irresponsible and undoable over here in the design world, then I'm lost here in the ideological reflection world because it's never going to get built. … I really feel like I have to have this tripod of three disciplines … the spark, the implementation, and the reflection. It's an interactive cycle.

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[13] Mechatronics is the incorporation of embedded microprocessors in mechanical engineering.

Epistemological strategies revisited

Researchers' descriptions of the ways in which they approach the integration of disciplines allowed us to identify three distinct epistemological strategies: Fluid integration, translation, and explicit integration. These strategies represented clearly distinguishable approaches to interdisciplinary work as viewed by our subjects. While most individuals tended to describe particular approaches, several referred to more than one approach over the course of the interview. This trend suggests that the strategies here described do not represent individual working styles that are consistently applied to all cases of interdisciplinary work. Rather, each strategy may prove useful at a particular moment of research.

Perhaps the early stages of a project require considerable explicit reflection about the goals, methods, and languages of the disciplines involved — an *explicit integration* approach. In contrast, once two disciplinarians are familiar with each other's modes of thinking, they may be able to focus on the account or the product that they seek to develop and intertwine modes of thinking more fluidly across domains — *fluid integration*. It is also conceivable that a team established to develop a product "keeps the eye on the prize" from early on, borrowing fluidly from various disciplines when necessary, without a reflection about the various disciplinary dimensions of the challenge at hand. Rather than stages toward increasing integration across disciplines, the three strategies here described may be viewed as part of a repertoire of moves to bridge disciplinary boundaries.

C. Cognitive skills

Throughout our interviews, researchers referred to a series of particular thinking skills that they often put to use when doing interdisciplinary work. They highlighted the value of establishing analogies, finding a common language, and reflecting upon the nature of knowledge and knowing in various disciplines. Researchers described how these skills allowed them to conceive of and pursue innovative work that often incorporates two or three bodies of knowledge.

1. Establishing analogies

A number of subjects across institutions referred explicitly to *analogy* as a common cognitive tool. They described how they used concepts from one discipline to shed light on comparable processes in another domain. “If you don’t tolerate analogies and metaphors, then you’ll never get anywhere,” claimed John Padgett matter-of-factly.

In a similar vein, when SFI researcher Doyne Farmer was working with a collaborator who was both a physicist and a computational expert to understand the analogy between markets and thermodynamics. Farmer asked, “How does entropy figure into markets?” The answer he arrived at was “analogical thinking.”

> 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. So there’s some randomness in their behavior … that creates something that’s like entropy and physical

> systems. So we're actually right now in a process of 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?"

Farmer explained that the analogy or metaphor provided the inspiration for a theory.

> 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.

Our subjects reported that establishing analogies allowed them to frame phenomena under study (e.g., markets) in novel ways. Some referred to analogy as an intrinsic mode of artistic thinking — one that, when applied to scientific problems, broadened conceptualizations. Paul DeMarinis, a new media artist who worked at PARC through the PAIR Project, described this contribution as follows:

> Art is in somehow the last throwback to analogical thinking, the pre- to neo-Platonism. … Artists still do think very much in the similitudes as laid out in the Renaissance. … It's a way of thinking that's very shot through, or it's been shown to be full of fallacy [in terms of] scientific reasoning but still is a very powerful tool for art … If you look at artists' work in the 20th century … you'll see all of these amazing kinds of reasoning cut off from science. It's really, really another world. … To really understand art, not just as gracious humanism … [but] to really have art stand alone and have a reason of its own to exist, I don't think you can ignore these backwards kinds of thought systems. … So I think this is where the point of dialogue between art and science really dwells.

Jim Crutchfield, whose work at the Arts and Science Lab centers on creating this dialogue, agreed that one of the ways to talk across disciplines is by using analogical thinking and metaphorical vocabulary. Yet he warned about the dangers involved in doing so. For instance, he described an evolutionary dynamics theory that has been metaphorically popular but mathematically incorrect. Such metaphorical thinking, he explained, may "lead to wrong intuitions."

> Initially, it is very helpful. A physicist goes, "Oh, I understand gravitational potentials! Therefore I understand evolutionary dynamics of optimizing fitness." Then it takes him six months to unlearn that misleading metaphor. The hill-climbing "landscape" metaphor is just not right. So metaphor can be good; we can start talking. Metaphor is sometimes useful. Sometimes there is even a useful misuse of words and misinterpretation goes in interesting directions. … But the sexier the metaphor, the more appealing it is intuitively, the more damaging and difficult to correct it can be.

In sum, analogical thinking seemed to serve the interdisciplinary mind by inviting researchers to borrow concepts or modes of representation from one discipline and establish parallels with problems in another one, thus illuminating aspects of the problems that would have remained unseen. And yet as an original member of the R.E.D. group, Steve Harrison (and Crutchfield) reminded us, whereas "analogies can help the artist see or think about something more widely," they can also "distort the seeing and so can be in the way of 'good' science."

2. Ability to speak a common language

In addition to analogical thinking, the interviewees in our study repeatedly cited the ability to forge and speak a common language with others as a prerequisite for successful interdisciplinary work.[14] As we described earlier, for faculty like Crutchfield at SFI, the common language spoken consists of theories of nonlinear dynamics and complex adaptive thinking that were built from a grammar of mathematics and mathematics-based modeling.

Among the members of R.E.D., the common language was design. Members shared an interest or background in art and aesthetics in addition to their technical skills. This aesthetic sense informed their individual and collaborative work and kept them involved in building prototypic machines even after the engineering or the programming work was finished. During the XFR exhibit work, the group's collective language was formed in the design review process or critique, sometimes known as the "crit." "Crit" involved long hours of continuous meetings evaluating the look, feel, usability, genre, and meaning of each exhibit.

Reflecting on this recent experience, Minneman reported that "there are huge language issues" in the interdisciplinary process. R.E.D. members succeeded in working through them because "we all were picking up bits of each other's language over the development of this collaboration." The key was:

> Knowing what to ask, … how to talk to your collaborators, and being able to get to some shared basis for reasoning through choices and doing design work with them … so that there's not too big a gulf to be crossed in order to figure out how to balance … concerns between electrical engineering, mechanical engineering, software, [and] writing.

At CIMIT, subjects considered the ability to find a common language in which to communicate across the fields of medicine and engineering as pivotal to the collaborative enterprise. Rather than seeking a formal shared language such as design, mathematics, or nonlinear dynamics, these researchers highlighted the role of everyday language as a tool to communicate across disciplinary boundaries. A long-time CIMIT collaborator asserted

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[14] See Peter Galison's discussion of the creation of common languages in *Image and Logic: A Material*

that no discipline is actually as complicated as its language makes it sound. In his view, specialized languages exist to make intra-disciplinary work more efficient and to signal membership in the disciplinary community.

Similarly, Reuben Mezrich makes it a point to avoid talking in intimidating engineering terms and ensure that the doctors involved in CIMIT projects have the patience to describe organs to engineers in something other than complicated medical terms. When professionals from both sides can meet each other halfway in the way they speak to and learn from each other, Mezrich describes how the results can be impressive:

> These wizards over at MIT have developed what they call an artificial muscle. It's a conductive polymer, and if you apply voltage to it, it contracts; if you turn the voltage the other way, it expands. … You can think of a lot of things [to do with this material], but think of … an artificial sphincter for people who have had … prostatectomies or diabetes or whatever, and simply can't control their urinary sphincter … .
>
> Well, the first thing we have to do is teach these guys [the engineers] what a bladder is and how it works. It was actually a great culture shock because the urologist came over and sat with the group at MIT — a group of mechanical engineers — and he started out drawing pictures … explaining what a bladder is, what the function of the sphincter is. … Then he started getting wonderful questions — they wanted the numbers: What is the flow velocity? What's the pressures? There was a great interchange… . That was a great example of the cultures being bridged on both sides.

In sum, whether by using a formal common language to bridge various disciplines or by favoring simple everyday language, interdisciplinary workers need to develop flexible communication skills. According to Newbower, they have to be good at communicating in their own disciplinary language. Researcher Maribeth Back says that interdisciplinary workers have to learn "how to talk to each other" and need "to be well-spoken and able to

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Culture of Microphysics (Chicago : University of Chicago Press) 1997.

talk about what their ideas are and able to get their ideas across in a way that's meaningful."

3. Metadisciplinary awareness

A third cognitive skill or strategy broadly referred to and exemplified by our subjects was the ability to think about the goals, methods, and forms of communication of particular disciplines — to reflect about the very qualities of disciplinary knowledge and inquiry. R.E.D.'s manager, Rich Gold, valued the ability to "go up one level and look." Marc Chow, who has experience in architecture, visual design, film, video and engineering, described this level as "seeing the constraints of all the disciplines at once." He argued that a metadisciplinary perspective kept him from going too far in the direction of any one particular discipline.

Metadisciplinary thinking enabled some researchers to "see" the particular roles and constraints imposed by individual disciplines in their projects. Matt Gorbet found that one of the benefits of interdisciplinary work is the ability it gives him to shape the way a project will look as he anticipates the various disciplinary constraints — while working on circuitry, he can also think ahead about design. He is able to tackle problems knowing simultaneously that solutions can be found any number of ways, saving time and headaches in the process. He can often become frustrated with "pure" designers who cannot see into the many levels of a project nor recognize their own partial perspective. He has participated in multi- or interdisciplinary ventures in which one member who doesn’t know or realize his or her disciplinary limitations insists that “there’s no way to do it” due to sheer ignorance of alternative approaches.

The ability to “move up one level” becomes critical in understanding the challenges of interdisciplinary work. Our interviewees often compared and contrasted disciplinary methods and validation criteria in order to shed light on the challenges and possibilities of cross-pollination among domains. For example, Steve Harrison described representations in art and design as traditionally metaphoric, ambiguous, and evocative – standing in sharp contrast to representations in science:

> Scientific representations, while abstract, are often mathematical and precise — or if not precise, the ambiguity is minimized by understanding the statistical certainty of the observation. The strictures of science constrain the range of acceptability: light is said to be like a particle or like a wave. [Science] does not admit imagining that light is like mashed potatoes or the scent of a rose. Peer review and special language work hard to establish the boundaries of acceptability.

Moving flexibly between this kind of epistemological analysis and concrete examples relevant to the problem at hand allows interdisciplinary workers to orient themselves and understand the unruly terrain that lies in between two or more disciplines. In Anne Balsamo’s opinion, a good interdisciplinary worker has to be “comfortable working across discourses, working across paradigms, working across disciplines.” Doing so requires an “intellectual flexibility … that comes with … experience when you’re able to shift from talking philosophically about something to talking about the nuts and bolts of programming.”

D. Dispositions, strategies and skills revisited

The dispositions, epistemological strategies and cognitive skills described above help paint a picture of how individuals approach interdisciplinary work. While individuals across the institutions illustrate various dispositions, strategies, or skills, it is worth noting that some institutions claim more of one approach than others do. A preliminary analysis suggests, for instance, that several of the subjects from SFI and the Arts and Science Lab claim to think in analogies while only two former R.E.D. members mention the same phenomena from the Xerox PARC population. Conversely, what predominates among R.E.D. members is their metadisciplinary thinking — being able to see the disciplinary constraints of a project. Translation to a formal language like mathematics is also a more common epistemological strategy among SFI researchers than among R.E.D. members. Translation to everyday language is a particularly common approach among CIMIT subjects, who often exhibited metadisciplinary awareness when helping forge collaborations between individual disciplinary doctors and scientists or when working between the disciplines themselves.

Individuals within each institution exhibited a broad range of dispositions, strategies, and skills. However, our observations suggest interactions between institutional contexts in which researchers work and the particular dispositions, strategies, and skills that they tended to portray. In our conclusion, we revisit these interactions and propose new research venues to understand the various forces shaping interdisciplinary work.

V. Conclusion

Interdisciplinary work — a multi-layered and complex phenomenon

The expression “interdisciplinary work” refers to work that takes place at the crossroads of two or more disciplines. It denotes both the way in which researchers and institutions organize professional life, as well as the particular nature of the intellectual enterprises in which they embark. In this paper we have examined the institutional and psychological dimensions of interdisciplinary work as described by innovators in five exemplary interdisciplinary organizations. We examined the particular kinds of institutional affiliations that our subjects embraced (e.g., local vs. virtual), we explored the nature of their institutional missions (e.g., *push* vs. *pull*), and we identified the qualities of collaboration or hybridization that proved productive and challenging. Intellectually, we characterized good interdisciplinary workers as embodying a disposition toward curiosity, risk-taking, open-mindedness, and humility. Finally, we discerned their overarching strategies to bridge disciplinary divides (seamless integration, translation, and explicit integration) and the particular skills that allow them to navigate the interdisciplinary terrain (analogical thinking, common languages, and metadisciplinary views).

Interdisciplinary work is defined by the act of borrowing and lending that takes place across disciplines. Researchers combine questions, concepts, theories, methods, and tools originating in different fields to address problems or create products that could not be approached by single disciplines in equally productive ways. In this cross-pollination, the institutional, psychological, and epistemological dimensions of the work interact. For example, physical closeness and SFI's organizational mandate to promote cross-pollination allowed John Padgett to meet the chemist whose theory would shed new light on our understanding of Renaissance Florence. SFI's institutional mission to search for fundamental patterns shared by natural, biological, physical, and social phenomena, invited Padgett to engage in the translation of historical data into computerized models of change. In other words, the institutional contexts in which this researcher worked seemed to play a significant role in defining the strategies that he and other individuals used to chart new territory.

Conversely, the epistemological requirements of the work also shape the ways in which people and activities are best organized. For example, the complexity of what is borrowed across disciplines determines the degree to which a project will require hybrid researchers or long-lasting collaborators in different fields. Using the concept of entropy in thermodynamics to illuminate aspects of market behavior in history may require a historian to understand the principles guiding the laws of thermodynamics and apply them to measure "efficiency" in a social system. In contrast, engineering a tool to produce the blueprint for the generation of a biological organ — as done by CIMIT member Joseph Vacanti and his colleagues at the Draper Laboratory — may require long-term collaborative work among molecular biologists, M.D.'s, and engineers. Compared to the concept of entropy, the know-how in engineering required for this project is less easily transferred to those outside the field.

Similarly, the goals and products of interdisciplinary work – whether in the form of explanatory theories, provocative exhibits, or useful demos — also impose constraints on what counts as an acceptable outcome. Scientists at SFI seek to understand and explain the work of complex systems in a variety of realms. Their accounts must satisfy standards such as appropriate formalization, explanatory strength, predictive power, and eventual empirical validity. In contrast, researchers at the Media Lab, R.E.D., and CIMIT seek to develop workable products. These products are assessed by more pragmatic criteria such as utility, functionality, effectiveness, and originality. Mark Chow captures the relationship between institutional mission and standards of acceptability :

> The way that R.E.D. looks at art, design, science, and engineering [is] very different than the way … an artist would look at it — or a scientist, for that matter, if you want to be closer to the technology. … We say that they're searching for the truth and [we're] searching for the workability. So the constraints are going to be set differently.

In sum, interdisciplinary work lives in the land that lies in-between disciplinary traditions. The land is defined by a multiplicity of perspectives, intertwining traditions, a loose sense of professional community, eclectic institutionalization, and undefined standards of acceptability. The excursions into this land captured in our paper speak to the challenge of conceptualizing this eclectic and multidimensional terrain. Interdisciplinary ventures vary greatly in goal, scope, and type. For instance, strategic alliance between art and technology may respond to an aesthetic motivation to critique our times or to a practical desire to address the needs of a society of the future. Interdisciplinary projects may enlist large teams of researchers or a committed pair of thinkers examining society in novel ways. Interdisciplinary projects may bring together fields that share a family resemblance like biology and physics, or fields as epistemologically distant as history and chemistry. Interdisciplinary collaborators may borrow from each other enough to solve a particular problem, or they may immerse themselves to transform each other's disciplines at the core. The diversity of ventures and discourses in which interdisciplinarity lives adds to the challenge of making sense of this mode of knowledge production and proposing an integrative framework to describe it. Recognizing this challenge, we propose some lines for future research.

Describing and explaining interdisciplinary work — a possible research agenda

As we proposed, describing and explaining interdisciplinary work involves understanding the social and organizational contexts in which it takes place as well as the epistemological transactions that make it possible. In our study so far, we have addressed three institutional dimensions of interdisciplinary work: locus of institutional affiliation, institutional mission, and degrees of collaboration. Two additional qualities loomed large in our data and remain to be addressed.

First, a study of institutional conditions should examine the role that leaders play in the research initiatives under study. In his study of highly creative groups, most of which were interdisciplinary, Warren Bennis highlights the central role of a strong leader as creator of and as created by "great groups."[15] Individuals like Nicolas Negroponte, Rich Gold, and John Parrish exemplify Bennis' pragmatic dreamers who are able to recognize talent when they see it and to sustain attainable visions over time. A further analysis of

[15] Bennis, W. and Biederman P. (1997). *Organizing Genius: the secrets of creative collaboration.* Addison-Wesley: Reading MA.

how they came to “curate” the talents under their management will complete our institutional profile.

The second area for further exploration is the role that broader societal forces may play in defining the goals, outcomes, and standards that validate interdisciplinary explorations. This work takes place in academic as well as in corporate contexts. It is funded by government agencies as much as it is by private foundations and corporations. Part of the corporatization of knowledge production taking place in the U.S. since the late 70’s has represented a shift toward shorter-term research projects and outcomes of visible applicability.[16] This shift has also demanded that researchers pay greater attention to the potential uses of their work — converting the public (e.g., present and future patients, consumers, and artists) into stakeholders. Because standards of acceptability are being defined through these broader shifts in knowledge production, understanding interdisciplinary work demands that we understand its relationship to sources of funding and to broader economic and societal forces.

Understanding interdisciplinary work relies to a great degree on understanding its epistemological complexity — the sources of its innovative power. Three main epistemological dimensions remain to be examined: (a) the process of borrowing across disciplinary boundaries; (b) the integration of knowledge, and (c) the definition of standards of acceptability. Understanding these dimensions and the relationships between

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[16] See Gibbons M. et al (1994). The new production of knowledge : the dynamics of science and research in contemporary societies. London: Thousand Oaks.

them will allow us to capture qualities of interdisciplinary work that move beyond the idiosyncratic features of particular projects.

(a) Borrowing across disciplines. Borrowing and lending across disciplinary boundaries may serve many purposes. For example, researchers at SFI may borrow computer models or dynamic theories to structure a relatively unstructured domain like history or to allow experimentation in domains that do not normally permit it, like biological evolution. One CIMIT researcher turns to molecular biology to produce explanations for the tissue behavior he observes. In the process of borrowing, researchers do not embrace the lending discipline as a whole. Rather, they tend to select particular concepts, theories, methods, tools, questions, and languages from it. Their challenge is to identify what is to be borrowed, understand it in its original context, and assess its role and viability in the discipline in which it is incorporated. For example, evolutionary biologists at SFI borrow mathematical models that allow them to carry out virtual experiments involving thousands of generations of a particular species. In doing so, they recognize and understand nonlinear models as the lens to be borrowed and applied to evolutionary phenomena. Any oversimplification of this lens would render the project invalid. Once the computer has produced results that indicate distinct evolutionary patterns, the researchers face the challenge of testing these patterns through yet another venue like molecular biology. What counts as a result in computer analysis becomes a hypothesis when placed in the context of evolutionary biology. It is to these shifts of epistemological status of claims that interdisciplinary workers must attend.

(b) Integrating disciplinary perspectives. Interdisciplinary work seeks to achieve synthesis or integration. Because we lack an appropriate language to refer to this synthesis, our subjects' descriptions often remained metaphorical, typically addressing territorial and organic metaphors. While considerable work is still to be done to unpack the nature of interdisciplinary synthesis, our preliminary analysis suggested three distinct synthetic modes. Still hypothetical, these modes of integration must be further explored.

First, researchers may integrate disciplines by focusing on modes of thought that cut across disciplinary boundaries. Examples of these modes of thinking include hypothetical-deductive reasoning, inductive and adductive reasoning, aesthetic appreciation, and pragmatic orientation. These modes of thinking certainly play out differently in each discipline. For example, while adductive reasoning is applied to biology and history, each discipline imposes a unique set of constraints to it. However, the synthesizing experience reported by some interdisciplinary workers suggest that it was easier to distinguish between aesthetic and empirical dimensions of their work than to recognize when one discipline ended and another one began. We hypothesize that what subjects referred to as "seamless integration" of disciplinary approaches may actually be referring to a different kind of categorization of knowledge and thought — one better characterized by terms like empirical, theoretical, heuristic, or practical.

A second integrative structure, we might speculate, is the one shaped by a single integrative framework. Complexity theory served SFI researchers as a powerful framing device. Dialectical materialism or Jean Francois Lyotard's critiqued meta-narratives may function comparably to describe economic, cultural, artistic, and sociological phenomena. Integrative frames of this kind shed light on particular categories and relationships that might otherwise remain unseen, allowing for fuller descriptions of a complex phenomenon. Under closer examination, we hypothesize that researchers who refer to their efforts to “translate” disciplines into mathematics or design may be revealing this type of integrative structure.

Finally, integration may take place through a careful and conscious weaving together of particular aspects of particular disciplines. Integration may look like a tapestry in which threads originating in various disciplines intertwine, creating a texture and structure that is unique to the particular interdisciplinary enterprise at hand. Researchers’ description of their work as a conscious shifting of disciplinary perspectives was suggestive of this deeper integrative structure. We hypothesize that further research in this area will reveal how particular threads inform one another. For example, robust frameworks in one discipline may prove to be exploratory metaphors in another or a source of hypotheses to be tested empirically in a third. Like the previous two modes of interdisciplinary integration, a tapestry model calls for a redefinition of validation criteria. No longer is it enough that a theory (e.g., thermodynamics) is well understood; its function and role in a novel context of application must be considered with care.

(c) Standards of acceptability. When interdisciplinarians explore the uncharted territories that exist between disciplinary boundaries, disciplinary standards no longer suffice to validate results and procedures fully. In part, this is because aspects of particular

disciplines such as theories or methods, once borrowed by other domains, adopt a different epistemological function. Borrowed theories or methods must be understood in their new contexts. In addition, because interdisciplinary work seeks to result in accounts or products that are more than the sum of their disciplinary parts, the often inscrutable "added value" must be captured in an intersubjective way.

The subjects in our study often referred to the difficulty of establishing standards of validation for interdisciplinary work. They mentioned the failure of the system of peer review, the lack of set parameters for excellence, and the difficulties finding publication venues. Validation is the least understood aspect of interdisciplinarity. Understanding its process and values may inform our understanding of interdisciplinary knowledge in practice — where eclecticism abounds, and particular goals and purposes set the bar for appropriate levels of sophistication.

The effort of validating knowledge using multiple disciplinary perspectives has a few precedents. In ethnography, for instance, researchers seek to ground their accounts in multiple sources of data that require discipline-specific methods of interpretation. That community has adopted three important strategies to enhance the validity of their accounts: a serious treatment of the disciplines involved (e.g., demography, art, history, anthropology), a softening of the epistemological status of results (i.e., results as well-grounded interpretations rather than "findings"), and an explicit reflection on the role of the ethnographer as knowledge constructor.[17]

[17] See J T. Klein 1990 *Interdisciplinarity : History theory and practice*. Detroit: Wayne State University Press.

The creation of any new domain provides another important precedent to the effort of building knowledge and validation criteria at the same time. In referring to this challenge, philosopher Catherine Elgin suggests that what makes for an acceptable epistemological framework is neither a set of rigid, pre-established disciplinary rules nor a community of consensus. Rather, acceptability depends on the goals of the enterprise and kind of excellence one is after. Advances in our understanding, she explains, do not happen as incremental growths of knowledge. Instead, a delicate process of adjustments and revisions takes place, whereby a new representation or a system of beliefs about a particular phenomenon is created. Elgin locates epistemological rigor in our ability to critique our understandings, revise them, and retry.

> If our considered judgement leads to an untenable conclusion — if, for instance, it generates false predictions or conflicts with more highly warranted claims — we retrench, retool, and try again. [18]

It is in this spirit of self-critique, retooling, and striving that we shall continue to examine the problem of interdisciplinarity. We seek to broaden our scope to encompass societal and institutional dimensions, as well as epistemological qualities of this type of work in addition to the individual experiences of the researchers carrying it out. We shall seek to deepen our analysis to produce explanatory frameworks that systematize, at least in initially viable ways, the unruly but seductive territory of interdisciplinarity.

[18] Elgin C. (1996) *Considered Judgement* New Jersey: Princeton University Press. p. 13