CHAPTER 6

Physical sciences

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Few more striking sites of interdisciplinary collaboration exist than the experimental hall of the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory on Long Island, New York. Synchrotron radiation is light given off by charged particles bending in a magnetic field. The light is emitted in a continuous spectrum and can be finely tuned, giving it a broad range of applications, from imaging biological tissues and determining chemical structures to etching computer chips. The NSLS contains two rings of electrons that emit such light: an ultraviolet ('U') ring with a radius of 51 meters that emits light through 17 ports, and an X-ray ('X') ring with a radius of 170 meters that spins out light from 46 ports. Each port is equipped with devices to customize properties of the light for specific techniques or purposes, and many ports are subdivided two or three times (Fig. 6.1). The researchers who interact on projects there are employed by a variety of institutions, including industry, universities, and national laboratories in the United States and abroad, and come from branches of physics, biology, chemistry, condensed matter, geology, environmental science, and medicine (Fig. 6.2).

Port X5, once the site of an experiment in nuclear physics, is sandwiched between two ports used for protein crystallography and for imaging polymers, artificial biomembranes, and other soft matter. Port X17 was converted from angiography to high-pressure geoscience. A diffraction enhanced imaging device at port X15A allows an optical physicist to work with medical researchers on producing sharp, 10-micron resolution images of soft tissue such as cartilage and ligaments (the team also works at Brookhaven's nearby MRI facility). An X-ray microfluorescence facility at port X26A for detecting trace elements is used by environmental scientists, Alzheimer's researchers, and scientists studying samples of interstellar dust collected by the Stardust spacecraft as it flew through the tail of Comet Wild 2 and returned to earth. The Stardust scientists, who include astronomers, chemists, physicists, and geologists, also used ports X1A, U10A, U10B, and ports at the other major synchrotron radiation sources in the United States. Scientists from Exxon Corporation use five ports (U1A, X2B, X10A, X10B, and X10C) to examine proteins, catalysts, and minerals. On the corridor wall adjacent to port U10B, used for infrared microspectroscopy, a bulletin board displays dozens of snapshots of the diverse international teams
who have used the port, including forensic scientists, art historians, volcano researchers, medical investigators, soil scientists, food scientists, and more.

The NSLS experimental hall thus illustrates a variety of ways that interdisciplinary research occurs in the physical sciences. First, it is a single facility that supports multiple projects in different fields. Second, each project, large or small, requires integration of knowledge, techniques, and perspectives from several disciplines or specialized subfields. Third, in a few instances the projects are helping to create new disciplines. Finally, many projects require more than a single instrument, and incorporate knowledge, techniques, and perspectives from additional facilities at Brookhaven and other labs.

The NSLS, and its interdisciplinary research progeny, arose not from any desire to be interdisciplinary for its own sake, but from the developing interests and specific goals of solid state researchers. What is distinctive about interdisciplinary research in the physical sciences as compared with that in the humanities is that the physical sciences do it more and without fanfare or self-congratulation, face the problems practically, and theorize about it less. Interdisciplinary research is seductively easy to theorize about, and can give rise to high-minded glorifications of ‘boundary-crossing’, ‘transgression’, and the production of ‘new objects’. Such talk can deliver the impression that boundaries are good to cross so long as they are on someone else’s property—NIMBY (‘not in my backyard’) interdisciplinarity, one might call it. Interdisciplinarity is more treacherous than it looks. The advantage of the case of the physical sciences is that interdisciplinarity can be looked at concretely in ways that can help to weed out much posturing and ideology.
6.1 History

Interdisciplinary research and collaboration is surely as old as science itself. In a three-part article in *Scientometrics*, Beaver and Rosen (1978, 1979) examined the entire history of scientific collaborations, including interdisciplinary ones, through a co-authorship study. Yet the scope and scale of what is done on the NSLS floor, and the impact on instruments, facilities, and techniques, are of recent vintage.

6.1.1 Emergence of interdisciplinarity

The beginning of the nineteenth century witnessed a disciplining of modern science, when it came to be conceived as consisting of relatively discrete and specific bodies of knowledge or 'logics'. However, this development was also accompanied by the recognition that the knowledge embodied in each discipline bore on others, and that understanding any particular slice of human life involved a spectrum of fields. These two poles are illustrated by Humphry Davy's famous introductory lecture on chemistry at the Royal Institution in 1802, in which he extolled the value of chemical knowledge for a multitude of sciences and throughout human life and experience, and by Michael Faraday's equally famous discourse at the same institution about half a century later, in which he showed that the complete understanding of a single, simple candle involves many different fundamental laws of nature, from capillary action to gravitation. When Auguste Comte propounded his scheme of classification of the sciences, he argued that while the division of intellectual labor was necessary and the disciplines would have to be separately cultivated, he also stressed that the sciences all belonged to a 'greater whole' and that any division was 'at bottom artificial'. He warned against 'too great a specialization of individual researches' as 'pernicious', because the end of science was to understand the world around us, which is inherently complex and cannot be addressed by any single discipline (Comte 1888, pp. 16–17).

Early interdisciplinary research projects often took the form either of researchers applying techniques (whether theoretical or experimental) cultivated in one field to another, or of researchers in one field working at the frontier of another. Warren Hagstrom (1964, 1965) compared early forms of collaborative research in science to medieval forms of economic organization. Professor–student relationships, for instance, resembled master–apprentice relations, while 'free collaborations' resembled medieval partnerships. The latter are initiated informally, and Hagstrom likened their initiation process to courtships in which suggestions of interactions are cautiously initiated and explored, often accompanied by fear of ejection (Hagstrom 1965, p. 114). But Hagstrom wrote that just as modern corporations have come to dominate both apprenticeships and free partnerships, so a more complex form of collaboration was arising that would soon dominate scientific research. The roots of this more complex and corporate form of collaboration, he wrote, were threefold: (1) centralization of authority imposed from above by institutions or funding agencies and by large and expensive facilities, access to which was necessarily restricted; (2) a necessary division of labor among various kinds of technicians and experts; and (3) interdisciplinarity, which can be contrasted with multidisciplinarity, or mere division of labor among disciplines.

Such more complex collaborations began to emerge early in the twentieth century. As Davy had prophesied, chemistry was often a principal ingredient of interdisciplinary collaborations in fields such as biophysics, physical chemistry, and chemical engineering. Other interdisciplinary fields to emerge in the early twentieth century included radiation science, which combined elements of physics, chemistry, engineering, biology, and medicine; and cybernetics, which brought together pieces of architecture, control systems, electronics, game theory, logic, mechanical engineering, neuroscience, psychology, and philosophy. Sometimes interdisciplinary projects were a function of the goal of a specific set of researchers, such as the famous BFFH astrophysics paper, 'Synthesis of the elements in stars', that sought to explain the formation of heavy elements in stellar interiors (Burbridge et al. 1957). At other times, interdisciplinary research was deliberately cultivated by individuals at funding agencies, such as Warren Weaver of the Natural Sciences Division of the Rockefeller Foundation (Kohler 1991). Interdisciplinary research often forced laboratories such as the Radiation Laboratory at the University of California at Berkeley, and projects such as astronomical and space programs, to devise efficient ways to handle it (Everitt 1992; Seidel 1992).

The discovery of the molecular structure of DNA in 1953 was an important landmark, and generated a special set of problems for researchers. One was a certain amount of disciplinary anxiety that biology was about to be colonized by other fields, leading to A. V. Hill's rejoinder that 'Physics and chemistry will dominate biology only by becoming biology' (cited in Pantin 1968, p. 24). It also inspired some rudimentary reflection about interdisciplinary research; Carl Pantin, for instance, was moved to propose what he called a 'real' distinction between restricted and unrestricted sciences, or those (like physics, he thought) that do not require investigators 'to traverse all other sciences', and those (like biology) where the 'investigator must be prepared to follow their problems into any other science whatever' (Pantin 1968, p. 24).

In the 1960s, when Hagstrom wrote, applied research, especially industrial research such as DuPont's, already tended to be interdisciplinary. 'Better living through chemistry' was then a popular advertisement of an advertising slogan adopted by the DuPont chemical company in 1935 and used for almost half a century to market its research and development projects across many fields (for the past decade the company has used the more generic slogan 'The miracles of science'). But Hagstrom remarked that interdisciplinarity was much less common in basic research. When it did exist, he wrote, it experienced strains of the sort that entail 'inherently heterogenous' emerging disciplines (Hagstrom 1965, p. 212), manifested for instance by behaviors such as obsequious celebration of a field's founders. Interdisciplinary work indeed can create not just disciplinary anxiety but also an intense kind of personal anxiety. When boundaries that have been taken for granted come to appear moveable, it not only opens the question 'What is the discipline?' but concomitantly the more personal questions 'What am I doing?' and 'Who am I?'

Today, the situation faced by Hagstrom has changed, and interdisciplinarity is common throughout basic research in fields such as addiction research, bioengineering, biological physics, biophysics, climate change, nanotechnology, and polymers. In 2000, the Nobel Prize for Chemistry was awarded to three scientists—two chemists and a physicist—for 'the discovery and development of conducting polymers'. In his acceptance speech,
6.1.2 Interdisciplinary instruments, facilities, and techniques

Interdisciplinary research has affected instruments, facilities, and techniques involved in experimental research by fostering their deliberate planning and construction. Many new devices and techniques, particularly imaging technologies, apply to more than one field. X-rays are a classic example; within 3 weeks of their discovery in January 1896, physicians had used them to help reset a child’s broken arm. But the scale and expense of modern instruments makes it necessary to maximize their constituency and design and promote facilities from the outset dedicated for interdisciplinary use. The NSLS—the first facility planned from the outset for synchrotron radiation research—is a classic example (Crease 2008a). Supercomputers are another.

Yet the impact of interdisciplinary on research takes still more complex forms. All experimentation is a species of performance; for it involves bringing together well-understood pieces of equipment and material in staging an event or series of events that seek to make some phenomenon appear, and let it be examined, in a way that would not otherwise be possible (Crease 1993, 2003). Staging performances requires production, or an advance set of behaviors and decisions necessary to assemble elements created for other purposes. The production of research equipment thus sometimes requires a kind of improvised engineering that John Law has called heterogeneous engineering (Law 1987). But the equipment of modern interdisciplinary research is of such a scale that not just pieces of knowledge and apparatus, but entire fields of knowledge are sometimes transformed and whole instruments reconstructed for new purposes, resulting in what Catherine Westfall has called recombinant science.

Recombinant science does not occur as a natural outgrowth of previous research, but involves researchers combining “insights and expertise from various subfields in new ways to create a brand new outlook” (Westfall 2003; Crease 2008b). In small-scale interdisciplinary collaborations, such as those commonly found at the NSLS, the end is generally a natural outgrowth of traditional interests, and the means require recruiting and coordinating researchers from different fields. Recombinant science, however, involves an entirely different story, in which the ends as well as the means have arisen as the result of contingencies and convergences that require researchers to adapt their intentions and methods, sometimes awkwardly.

6.1.3 The example of the RHIC

A case study in recombinant science is the construction of the Relativistic Heavy Ion Collider (RHIC), a $1.5 billion nuclear physics facility at Brookhaven, located not far from the NSLS but an entirely separate facility. It sprang from a high-energy physics proton collider named ISABELLE, on which construction began in 1978 (Crease 2005a, b). But serious problems caused the US physics community to lose enthusiasm for the ISABELLE project (briefly renamed the Colliding Beam Accelerator or CBA), and it was terminated in 1983. In a remarkable turn of events, the facility was converted into a facility of a new sort to explore a new field, relativistic heavy ion physics. To justify this transition, scientific subfields were invoked that did not exist at the time of ISABELLE’s birth, and the transition was made possible by certain key hardware components that also did not exist when ISABELLE was conceived. The new field of heavy ion physics effectively blended, initially with difficulty, nuclear and high-energy physics (Crease 2008b).

6.1.4 The age of interdisciplinarity

Why has interdisciplinarity become so routine in the physical sciences? Several theories have been advanced.

One, advanced by Hagstrom, is corporate; the scale of scientific projects and facilities now requires corporate-style organization and management in which different disciplinary components are coordinated (see Stokols, Chapter 32 this volume). Indeed, such organizations have now been around long enough that their patterns have developed. In their study of multi-institutional collaborations, for instance, Shrum et al. (2007) identified five different patterns of collaboration formation and four organizational types of collaboration, and note several bureaucratic features that have evolved to stabilize such interdisciplinary research.

Another theory, advanced by historian of science Paul Forman (2007), is epochal; the rise of interdisciplinarity is tied to the shift from modernity to postmodernity. The assumptions of modernity—especially the priority of theory over practice, of basic over applied research, and of disinterested over interested knowledge—produced the traditional disciplinary borders, and served to reinforce them. These disciplinary structures have all but collapsed as an inevitable consequence of the reversal of the priority of science and technology characteristic of postmodernity, with its ‘pragmatic-utilitarian subordination of means to ends, and of the concomitants of that predominant cultural presupposition, notably disbelief in disinterestedness and condescension toward conceptual structures’ (Forman 2007, p. 2).

A third theory is historical; that two seminal events—the development of quantum mechanics and the massive expansion of computational power—made interdisciplinarity both possible and inevitable. Quantum mechanics forced the reworking of the foundations of physics, chemistry, biology, materials science, electronics, thermodynamics, and other fields. It provided scientists with the confidence to claim that enough was known about the structure of matter so that, even if only in principle, large-scale substances and many real-world behaviors could be traced back to, if not entirely explained by, small-scale structures and forces. And the sciences of these large-scale substances and real-world behaviors—from proteins to superconductors—were not abstract domains like particle physics or cosmology but inherently interdisciplinary ‘real-world’ systems.

The expansion of computational power, meanwhile, also transformed nearly all the physical sciences not only through codes and calculations—which have often made it possible to trace back the behaviors of large-scale substances to small-scale structures and forces—but also through data analysis and fitting, search techniques, simulations, visualization
methods, and other tools. This has led to what Wilson (1984) called the 'computerization of science'. It also led to the interdisciplinary field (applied mathematics, computer science, and science and engineering) of computational science and engineering (CSE) which itself is a field that participates in other interdisciplinary fields (on its impact just on physics see Landau et al. 2008). Computation has also profoundly affected disciplines outside of the natural sciences, including art. Recognition of the relevance of mechanics and optics to painting dates back at least to Leonardo da Vinci's *Treatise on painting* and Hermann von Helmholtz's lectures *On the relation of optics to painting*. Yet the recent expansion of computational power (plus technological developments such as the development of selective laser sintering devices) has transformed the practice of artists in striking ways, such as in the recent emergence of the field of 'mathematical sculpture' (Grossman and Hart 2008; Zalaya and Barrall 2008), which includes representations of four-dimensional objects—the creation of a 'new object' if there ever was one (Fig. 6.3).

Yet a fourth theory offers a Comtean-style teleological explanation involving the purpose of science itself. The point of science is to allow the prediction and control of nature, and if we have divided science into disciplines it is only so that we can better cultivate them to the point where we can do this. We have had a learning curve while the disciplines were being cultivated, but at last we can bring them together again in interdisciplinary research. Any obstacles to so doing are the result of what Comte called the 'pernicious effects of an exaggerated specialist'.

For whatever reason—corporate, epochal, historical, or teleological—interdisciplinarity is here to stay. Many people have referred to the 'frontier of complexity', whose manifestations include biotechnology and nanotechnology, and which ensures that interdisciplinary research will dominate the natural sciences in the twenty-first century, a period sometimes referred to as the 'Age of Interdisciplinarity' (Marburger 2008).

### 6.2 Practical issues

Promoting the growth of interdisciplinary research is surely a fine goal. But as the Spanish proverb says, it is one thing to speak about bulls and another to be in the bullring. Fortunately, scientists and science administrators have had decades of experience trying to meet the concrete and practical challenges of interdisciplinary research. One speaker at a 2006 American Association for the Advancement of Science (AAAS) workshop on quality assessment in interdisciplinary research prefaced his remarks by recalling US President Grover Cleveland's blunt remark, in vetoing a tariff bill, that 'This is a condition we face, not a theory'. Interdisciplinarity is indeed a condition with pressing challenges that often do not respond nicely to theory. Its challenges vary throughout the phases of a project such as the construction of a big facility—from construction to operation to data analysis—and are also different for theoretical research. Practical challenges of the condition of interdisciplinary research in the physical sciences include coordination, quality assessment, communication, and culture.

#### 6.2.1 Coordination

One set of practical issues arises in laying out the conditions in which the various disciplines can work comfortably. Again, the example of the RHIC is illustrative. Nuclear and high-energy physicists would not only have to learn and adapt techniques from each other, but also learn to work comfortably together—yet their existing practices were quite different, using different kinds of instruments and different sized teams, with nuclear physicists used to working with a handful of collaborators, and high-energy physicists used to collaborations of dozens or even hundreds. At a key meeting at the beginning of the project, Arthur Schwartzschild, the chairman of Brookhaven's physics department, outlined a plan to address the problem by initiating an interim program of heavy ion physics at existing facilities at the lab that would run while RHIC was under construction. This, Schwartzschild said, would address the looming 'manpower and sociology issues' by 'building a constituency for collider experiments, effecting collaborative efforts between nuclear and particle physicists, and providing an appropriate arena and stimulus for detector development necessary for collider experiments.' In an interesting unwitting echo of Hagstrom's relationship metaphor, Schwartzschild concluded by saying that 'The new physics calls for a marriage between nuclear and high energy experimenters, and this conference looks like an engagement party to me' (Ludlam and Wegner 1984, p. 377c).
Erik Fisher and David Beltran-del-Rio

The relationship that distinguishes between multidisciplinary and transdisciplinary is also possible to think of as a discipline that lies at the root of other disciplines. In many different disciplines, from the natural and physical sciences to the social sciences and fine arts, it can also support knowledge integration across disciplines. Furthermore, developments in mathematics can be correlated to other disciplines - like the case of Kurt Godel's incompleteness theorems and postmodern theory (Thomas 1999). Mathematics can be thought of as a foundation for other disciplines both because of its descriptive applicability to a wide set of phenomena, practices, and developments in many other fields of learning and human endeavor and because it represents a fundamental form of knowledge.

Mathematics, from the ancient Greek mathēmatikē (that which can be learned), was originally broader than modern use implies. It encompassed all knowledge not just that which can be characterized through number. In modern usage, however, mathematics can be defined as the study of patterns and order within structure, space, and change. It employs logical reasoning and quantitative calculations to make statements that can be shown to be true or false based on first principles or axioms and rules of inference. Mathematics is considered "pure" and outside of the natural sciences useful as it investigates the properties of and relationships among idealized objects. Yet insofar as the knowledge it generates approximates physical phenomena, it can aid in their conceptualization and control, and can thus be considered applied.

Mathematics is generally considered to have originated prior to any clearly written historical record with practical problems, mostly involving commerce and agriculture, eventually extending into natural science and military applications. In the European tradition, pure mathematics arose much later, with Pythagoras (c. 550-475 B.C.). However, emergence of the mathematical study of natural phenomena did not historically coincide with mathematics. Aristotle (384-322 B.C.) developed a phenomenological science of nature based on understanding four distinct causes of natural phenomena, with mathematics being merely one mode of causality.

Mathematics played a more prominent role in ancient astronomy than in physics. In the cosmology that framed scientific thinking before the sixteenth century, the celestial sphere on which the moon was thought to travel defined a division line between heaven and earth, with the corporeal and impenetrable beneath this line, where the heavens were a realm of perfection and perfectly circular motions. Hence, early astronomers, particularly Claudius Ptolemy of Alexandria (c. 85-165 A.D.), concluded that mathematics, as a tool to describe heavenly motion. Ptolemy's insistence on viewing only perfect circles required him to employ epicycles, circles whose centers moved upon the circumference of larger circles centered nearly (but not exactly) on the position of the earth and around which orbital paths revolved. Likewise, mathematics was considered largely inappropriate for the study of sublunar phenomena, since a perfect tool could not describe an imperfect, corruptible world. Such a view of mathematics limited its interdisciplinary potential perhaps intentionally (Boethin 1998).

It was Galileo Galilei (1564-1642), who first clearly grounded the study of nature in mathematics. The Galilean revolution is often taken to involve his acceptance of Copernican heliocentric cosmology and insistence on experimentation and empirical "proof" of physical theories. Of even more importance, however, was Galileo's application of mathematics to sublunar motions and his insistence that physics should not seek causes, as Aristotle held, but generate only mathematical descriptions of natural phenomena.
questions. Economic and risk assessment methods such as cost-benefit analysis and probabilistic risk assessment are presented as tools for moral and public policy decision making.

The modern notion of mathematics as a core interdisciplinary has nevertheless been challenged on a number of levels. Jacob Klein (1889-1978) argued that the ancient Greek understanding of arithmetic differed importantly from the modern understanding of 'number'. According to Klein, arithmetic always means a definite number of definite things, whereas the modern 'number' replaces 'the real determinations of an object with a possibility of making it determinate' (Klein 1932, p. 123). The symbolic characteristic of 'number' is based on seemingly paradoxical assumptions: the logical status of mathematical objects is that of incomplete, independent 'things' with a mind-dependent concept, namely, quantity.

This brief history of mathematics suggests that the application of mathematics to other domains is partially a function of how mathematics is considered to be. Moreover, different conceptions of what counts as knowledge have at various times both limited and enabled the integration of mathematics within these other domains. The excessive modern employment of mathematics in describing and predicting phenomena can on the one hand be taken as evidence of the primacy of mathematics as a form of knowledge, and on the other counts as the cost of other forms of description and ways of knowing. In this case, at least, interdisciplinary success appears to be rooted in what constitutes the discipline.

References

6.2.2 Quality assessment

But such relationships still need to be monitored for their long-term health. In 2008, Boix Mansilla and Gardner wrote that a re-emerging awareness of interdisciplinarity as a pervasive form of knowledge production is accompanied by an increasing unease about what is often viewed as "the dubious quality" of interdisciplinary work. One factor is that the traditional method of quality assurance—peer review—can prove difficult in practice in the absence of true peers. A step in alleviating this concern, the authors continued, is to develop suitable processes, criteria, and contexts for assessing interdisciplinary work, including ways of selecting appropriate reviewers and of effectively managing their collective expertise in review sessions. One must find, as Martin Blume, the former Editor-in-Chief of the American Physical Society put it at the AAAS quality assessment meeting mentioned above, "referees who have open minds and a deep knowledge of the field". Among the problems is 'a tendency of physicists to believe that another area of science is not significant until it can be understood in terms of the techniques of physicists, and for, say, economists to believe that physicists have nothing to teach them' (Blume 2006). Another problem involves metrics for evaluation, such as citation counts or publication in high impact factor journals, for different fields may be of different sizes and differ too, in the shelf-life of influential articles. Groups such as the Council of Environmental Deans and Directors of the National Council for Science and the Environment provide online resources for interdisciplinary hiring, tenure, and promotion (CEDD 2008).

Other special measures that may be required to ensure the quality of fields include making sure that the appropriate spectrum of journals turns up in citation indexes; that once articles in journals such as Physical Review and Physical Review Letters become relevant to medical research, for instance, these journals are listed in Medline. Special awards for interdisciplinary research may be necessary to ensure that noteworthy research that may otherwise slip through the cracks is appropriately recognized. The New York Academy of Sciences, for instance, sponsors an annual award, the Blavatnik Award for Interdisciplinary Research. And interdisciplinary research poses special problems for librarians and information scientists: 'It is imperative for information scientists to understand the characteristics of interdisciplinary research and the researchers' information need(s) to better serve the scientific community' (Tanaka 2006, p. 41).

6.2.3 Communication

Thomas Kuhn famously argued that disciplines are defined by paradigms. If so, then any crossing of disciplines can only be either undisciplined, or a trade or exchange of something between disciplines: multidisciplinary rather than interdisciplinary. How is genuine cross-communication possible? Peter Galison provided a twofold answer involving the claim that paradigms are not that monolithic plus the idea of a trading zone, or special kind of place where different cultures meet and interact. What takes place in such a zone, he claims, is not 'translation' with its implication of one-step transpositions of meaning from one holistic context into another. Rather, local languages emerge—inter-languages, 'pôgins and creoles'—that 'grow and sometimes die in the interstices between subcultures'. In this way, 'trading partners can hammer out a local coordination, despite vast global differences' (Galison 1997, p. 783; Collins et al. 2007).

6.2.4 Culture

But interdisciplinary research involves more than language. Seligman et al. (2008) point out that, in genuine communal interaction, it is often more important to examine what people do rather than what they say or mean. One must beware of overgeneralizing the world, of overemphasizing the efficacy of language and belief in human action. Despite the detached, third-person style of research papers, what matters is not whether the result is epistemically justified, but whether the goal has been reached. The language of science is subservient to the practical requirement of achieving its goal. This signals the importance of another set of subjects critical to interdisciplinary research—its 'inmaterial culture', so to speak—including trust and expertise, to be mentioned below.
Cooperation, for instance, may require overcoming cultural differences, not just learning a new language. An example is provided by what happens to Stony Brook University computer engineer Steven Skiena each time he teaches his graduate course in computational biology. The two largest groups who take his class are biologists and computer engineers, and these have diametrically opposed backgrounds, experience, interests, and educational attitudes. From the beginning, it was difficult. The biology students took for granted the existence of a strict hierarchical pecking order that leads from professor to postdocs to grad students to lab assistants to undergraduates, and assumed that they must start at the bottom and work up. The computer students, by contrast, saw no such hierarchy, described themselves simply as working in the "Skiena lab," and treated everyone as peers, including Skiena himself. The biology students tended to feel violated if asked to program a computer, and computer engineers tended to feel likewise if asked to learn something about proteins (Crease 2006, p. 226). It is two disciplines, one might say, divided by a common subject. Skiena must get the class at least to mingle intellectually. He begins by mirroring back these cultural differences in a slide (Fig. 6.4). The PhD students in this class tend to retain their disciplinary affiliations after graduation—the computer science students tend to get jobs in computer science departments, the biologists in life science departments—which no doubt is a function of teaching, tenure, and funding factors. However, they do tend to wind up publishing or co-publishing much more in the other discipline—thus engaging more in interdisciplinary work—than their disciplinary peers.

5.3 Theoretical issues

What's distinctive about interdisciplinary research in the sciences, I said above, is that they do it more and theorize about it less. Scientists are accustomed to redraw their disciplines, and live and work with their boundaries under reconstruction. The practical, goal-oriented focus of the researchers allows them to bypass the need for reflection and metasubjective inquiry. Moreover, theorizing about scientific practice is the task of other kinds of scholars.

5.3.1 Disciplines and interdisciplines

One way to understand interdisciplinarity is through understanding disciplinarity. What constitutes a discipline? Objects? Methods? Concepts? Culture? Are the RHIC researchers, and NSLS researchers, actually being interdisciplinary, or merely retreading within what essentially the same large discipline of physical science? And is interdisciplinarity in the physical sciences different from what happens in social sciences and the humanities? Are there different kinds of boundaries? Examining such questions using case studies from the physical sciences can help clarify what we mean by a discipline.

A realist conception of disciplines would picture science as seeking to describe territories of knowledge or of objects that are out there independently of how we come to know them—where nature is divided at its joints. If we make changes in what our sciences
encompass we are correcting these boundaries to be more in accord with what is out there, rather than transforming the sciences or acting interdisciplinarily. In this view, the skeptics are right, and interdisciplinary research is arbitrary, hybrid, a disciplinary mule—sterile, not creative, and dependent for its continued existence on further seminizations. But it has proven difficult to differentiate disciplines by their global object, or what the scholastics called their material object. Each discipline comes at its objects in a different way, so the disciplinary objects differ—what the discipline sees in the global object is based on the discipline's own ways of investigating. Indeed, there seem to be only nominal and historic differences between physics, chemistry, biology, and so forth, in their terms of their formal objects.

For this and other reasons, following the appearance of Kahn's *Structure of scientific revolutions*, we have seen the emergence of what might be called a postmodern conception of interdisciplinarity, exemplified by Forman. In this view, the boundaries of disciplines are essentially arbitrary, as a function of how these sciences emerged and the social forces exerted on them, susceptible to change as these forces change. We created nature's joints. Indeed, if the disciplines make any attempt to resist the transformation of their boundaries they become suspect as ideologies, subject to a hermeneutics of suspicion of their justifications of their interests, claims, and narratives. The postmodern conception of disciplinarity valorizes, even celebrates, interdisciplinary work and its heterogeneity.

A third possibility is a *hermeneutical* conception of disciplines, in which the sciences are about the world as it presents itself to us and with which we are creatively engaged through our laboratory experiences. The world does not present itself to us as undifferentiated, but as being landscaped, certain of its regions being nearer or farther from others. We inherit, adapt, and transform this landscape—you first have to recognize and accept boundaries in order to reorganize or transgress them—both the areas comprising it and how these are related (Ginev 1997, 2006). When X-ray instruments first appeared, they could be used in different fields without significantly affecting the boundaries. By the time of the NSLS, however, the engagement with nature to which X-ray technology belonged—the scales and energies involved—had been sharply altered. The NSLS was not simply a bigger X-ray bulb in the same landscape; human beings and nature were positioned very differently in a changed landscape.

### 6.3.2 Trading zones

Another path to understanding interdisciplinarity involves looking at what happens in interdisciplinary projects. Collins et al. (2007) sought to develop a more general form of Galison's notion of trading zones, or places where different cultures interact. Noting that in the absence of communications problems there is only trade, they defined trading zones as 'locations in which communities with a deep problem of communication manage to communicate'. How, then, can such a 'deep problem of communication' be overcome? In several possible ways, say Collins et al., depending on the kind of trading zone it is. They propose a four-fold division of such zones by mapping interdisciplinary collaborations onto a graph with two axes. One involves whether the collaboration is cooperative or coerced, the other whether the end product is a heterogeneous or homogeneous culture (Fig. 6.5). In this way, the creation of new scientific disciplines like astrophysics, biophysics, or relativistic heavy ion research is only one of several possibilities for interdisciplinary collaborations. But the diagram is based on the assumption of a neat distinction between cooperation and coercion—which reminds philosophers of the old Aristotelian distinction between natural and enforced motions, and inspires wonder about the grounding of this distinction. How is this distinction reflected in scientific practice? Is the interaction between nuclear and high-energy physicists at the RHIC collaborative or coerced? On the one hand, the interaction moves scientists towards a goal—further understanding particles and nuclei—that they have always sought, which might suggest collaboration; on the other hand, it was political necessity for the laboratory, stitched together because of the failure of a big science project, which might suggest coercion. When someone makes the claim that the collaboration was cooperative or coerced, who then is speaking and why? The collaboration was both cooperative and coerced at the same time, or neither; it arose from the scientists living in the midst of the scientific world, motivated by dissatisfaction, and using what tools they had to achieve what they could in pursuing their inquiries. They were making their way intelligently in an atmosphere whose elements were not separable into categories like 'cooperative' and 'coerced'. Maintaining cultural heterogeneity is not always natural, and transforming it is not always slavery. The notion that all transformation of the boundaries of science is enforced is the product of a Forman-like postmodern conception of disciplinary boundaries.

What if interdisciplinary research, instead, were looked at from the perspective of its participants themselves, rather than from the outside? For someone joining a RHIC collaboration, say, it is not a matter of contributing a block of information to the project the way that a jigsaw piece contributes to the whole. Rather, it is a matter of working with other participants, oriented toward the practical realization of a goal. Being in such

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<td><strong>Collaboration</strong></td>
<td><strong>Fractionated</strong></td>
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<td>Inter-language</td>
<td>Boundary Object</td>
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<td>Biochemistry</td>
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<td>Nanoscience</td>
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<td><strong>Coercion</strong></td>
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<td>Subversive</td>
<td>Galley Slaves</td>
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<td>McDonalds</td>
<td>Use of AZT to treat AIDS</td>
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<td>Relativity</td>
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Figure 6.5 A general model of trading zones. From Collins et al. (2007).
a project cannot be conceived of in terms of a space of disciplines or departments but is rather more like participation in a community, with the life of the community determining and altering its structures rather than the other way around.

6.3.3 The immaterial culture of interdisciplinarity: trust and expertise

Interdisciplinary collaborations thus involve a matrix of intangible elements. To collaborate, you do not have to share the culture, or the same understanding, of the project on which you are collaborating; less tangible elements may come into play (Seligman et al. 2008, p. 8). All that may be required for one to help build or operate an X-ray machine may be things like a desire to help out. To be sure, this matrix and these less tangible elements tend to be drowned out by the task, the topic, the goal, and it is difficult to speak about something that is so easily overwhelmed by the discourse of facts and results. But these things are part of the atmosphere that allows us to inquire and act intelligently.

One of these elements is trust. Trust is a key, if often overlooked, concept in science. Trust here does not mean a moral virtue. Rather, to put it briefly, trust means deferring with comfort to others, in ways sometimes in our control, sometimes not, about a thing or things beyond our knowledge or power, in ways that can potentially hurt us. Trust, which has both a cognitive and a non-cognitive dimension, is extremely important in different kinds of interactions within science and between science and society. Science depends on trust in the form of all those bonds of mutual cooperation that have to exist between scientific colleagues in their various roles. Skurn et al. (2007) note the importance of trust in interdisciplinary collaborations.

The correlate of trust is expertise; an expert is often the one to whom one defers to obtain knowledge on which one is dependent. Collins et al. (2007) describe `interactional expertise', or fluency in the discourse of a field without the ability to contribute, as a particular kind of expertise necessary for at least one of their four categories of interdisciplinary collaboration. One of their key examples is Steven Epstein's (1996) description of San Francisco AIDS activists, who collaborated with researchers. Shall we call this a collaborative or coerced interaction? Here, too, the inquiry's the thing, and the activists' recognition of the need for scientific expertise is behind the interaction. When there is no common inquiry—antinuclear activists versus a research reactor, say—and the atmospheres are fundamentally different, interactional expertise cannot happen. Expertise breaks down in the absence of trust and a shared life-world. Without that shared life-world, there is the possibility of reading the meaning of that expert advice differently—that the experts are hired guns, misguided, ignorant, ideologically or politically motivated—conspiracy theories thrive, and the value of expertise vanishes.

6.3.4 Fractionation

Many studies have discussed the fractionation of fields of knowledge under various rubrics: internal differentiation, cross-stimulation, clusters of specialization, hybridization, and so forth (Tanaka 2008, p. 24). Collins et al. (2007) note that while many fields, such as that of gravitational wave detection and, we might say, relativistic heavy ion research, appear from the outside to be coherent, when viewed more carefully they can be seen to be divided into numerous subspecializations with no move toward homogeneity—that there is discontinuity when looked at closely. They propose that this may well be the real state of all science—that it is like a surface that seems smooth to the naked eye, but turns jagged when magnified enough. It may be that, when examined closely, what appear to be integrated networks of scientists are really conglomerations of small groups bound together by rich interactional expertise' (Collins et al. 2007). They add, `One can always choose to "zoom in" on any area of social life and, as the scale increases and ever more detail is expected, as a polished metal surface, what appeared smooth turns out to be jagged.' In this event, they claim, scientific disciplines are like `fractals' whose structure is renegotiated at every scale.

This interesting observation raises many questions. Is the fractionation of the same type throughout science, or does it vary throughout the phases of a construction project like that of a giant telescope or accelerator? And is there a limit to this behavior? Ian's research `quantized', in the sense that a `basic unit of research is the researcher, who builds expertise and competence by being cultivated in a particular area in a particular kind of research context'? That person's career and advancement are also determined by rewards and institutional structures, which also seek to keep that person focused on individual areas. This focus on individual areas may thus be for social reasons—prestige, advancement, coping with the administrative structure. The researcher may eventually join with others in a goal met jointly, but begins by mastering one area or set of areas. Research involves not the achievement of a collective objectness but an endless task of integrating and splitting in a communal context. Research is dominated by the practical goal at hand, whose attainment is often negotiated rather than solved like a puzzle. Solutions are always changing, giving rise to new kinds of goals with new expectations of attainment. Research takes place in a 'plain we do not totally control, one that is always also open to the other, to strange and different, beyond power of the center' (Seligman et al. 2008, p. 21). Adapting Whitehead's famous remark apropos of the way science treats its founders, we might say that a science that hesitates to move its boundaries is lost, but add that one that seeks to abandon them is lifeless.

6.4 Integrative systems

The interdisciplinary research described above involves regions of knowledge and interactions between researchers. A different, though related, set of issues is raised when such knowledge is considered as arising within `integrative technological systems' that have been planned and promoted for practical applications. Now not only scientists but also administrators, politicians, evaluators, lawyers, and businessmen are involved in a nexus that Klein (Chapter 2 this volume) calls transdisciplinary. A classic example is the Biopolis, established in Singapore, to promote not just medical research but also interactions with clinical applications, and to facilitate the construction of a proper legal and economic infrastructure in which these applications will thrive.
Rudiger Wink, for instance, refers to *innovation systems* and integrative technologies, by which he means 'the systemic linkages between single innovation networks to enhance interaction of knowledge between the networks and their members and to increase the innovative capacity of the whole system' (Wink 2008). These systems connect abstract and theoretical scientific knowledge with 'incumbent technologies', involve 'no clear boundaries between basic and applied science' insofar as new scientific knowledge can be plugged directly into new goods and services; and involve scientists serving as researchers, managers, and entrepreneurs. Such systems encompass the 'whole knowledge production process', or the entire 'knowledge value chain', extending from knowledge production through review and exploitation, in which the laboratory is only a part—but the rest of the system's effects what happens in the laboratories. Wink stresses the importance of *gatekeepers* as the connections between the elements of this process—the parallel to interdisciplinary research—and notes facilitating factors such as cognitive, social, and organizational proximity.

An example of integrative systems at work is human embryonic stem cell research. Here a science with a variety of direct and urgent practical applications is subject to a variety of regulations that cannot be ignored in research, and with huge effects on laboratory research, involving ethics, capital markets, intellectual property rights, and so forth. Different countries have different integrative networks for dealing with stem cell research with different kinds of legal frameworks, and different kinds of links to industries, in play that affect how research takes place. A country's integrative networks may facilitate or hinder its ability to link with networks in other countries.

Justus Lentsch, meanwhile, discusses the need to develop better *boundary institutions* that are accountable both to scientists and to policy makers (Lentsch 2006). Frequent cited examples of institutions with such *dual accountability* include the Dutch Sector Council Model, the European Food Safety Authority, and the European Environment Agency.

### 6.5 Interactional networks

Even more issues are raised when the public reaction to an integrative network is taken into consideration. A vast distance exists between the knowledge about a subject that circulates in a laboratory and the knowledge about the same subject among the public. A gap exists between the 'load' as it were, born by the discourse in the two cases (Crease 2000). Connecting the two requires a kind of 'impedance matching', in which the load is stepped down. This cannot be a one- or two-step process—education plus science popularization, say—but requires an entire spectrum of *interactional networks* between discourses with different loads. Without it, in public controversies with a technical dimension, positions become not argued but dramatically presented by people who think in slogans and communicate in images. Anti-biotechnology protesters dress up as Frankenstein monsters, protesters call shipments of low-level radioactive wastes 'mobile Chernobyls' while carrying placards of the skull-and-crossbones—actions which serve to displace, in public arenas, those who would argue or inform. The issues—especially highly significant ones like genetically modified organisms, nuclear power, the safety of low levels of toxins, and the ethics of stem cell research—are treated as if they were entertainment, and the public is effectively precluded from engaging them. The German philosopher Jürgen (Habermas 1989) refers to such patronizing tactics as 'a refudalement' of the public sphere. Interactional networks attempt to overcome such refudalement, requiring yet another kind of interdisciplinary activity, one that reaches not from one discipline to another but from one way of life to another.

### 6.6 Conclusion

The physical sciences present excellent case studies of interdisciplinarity, its problems, and its prospects. Interdisciplinary research in the physical sciences is a particularly interesting case because of the amount of experience, the practical challenges, and the theoretical issues it raises in connection with science and its practice. Theorizing about interdisciplinarity can involve considerable posturing and self-congratulation. The physical sciences present clear examples of the inheriting, adapting, and transforming of disciplines—which can transform not only our understanding of science but also of all research. Interdisciplinary research is not simply changing science—its disciplines and the boundaries between them—but forcing the question of what science itself is. Its boundaries are shifting, in ways that make us mindful that it could have been otherwise, and doubtless will change still more in the future. And interdisciplinary research in the physical sciences, its integrative systems and interactional networks, is becoming ever more important to the welfare of the planet, making its study essential. Sites such as the NSLS floor would be a good place to start.

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### References


Integrating the social sciences: theoretical knowledge, methodological tools, and practical applications

CRAIG CALHOUN AND DIANA RHOSTEN

The distinctions among the social science disciplines are historically forged and largely arbitrary. Nonetheless, they are reproduced not only in boundary struggles but also in the training of graduate students, the writing of textbooks, and the review processes of scholarly journals. They may be more matters of style than method—characteristic structures of attention, values, and ways of solving problems—but they are also maintained simply by habit and social networks.

By contrast, it is common to speak of physical sciences in the singular. The common scientific method suggests unity despite the differences among disciplines. There is tacit commitment to commensurability in science (Wilson 1998). There is no analog to expectation in the humanities, but instead a celebration of different perspectives. University arts and humanities faculties are always plural, a reflection of divergent methods as well as topics. Oddly, these are both responses to the decline of theological authority. On the one hand, a new unity emerges, and on the other, the recovery of a classical idea of multiplicity of liberal arts, each distinct as a craft skill, is itself a universalism. In this as much else, the social sciences occupy an in-between position. Since the methodenstreit of late nineteenth-century Germany, the social sciences have been torn by recurrent struggles over scientific universalism versus humanistic particularism.

In any case, social scientists have divided increasingly between those who understand human behavior as a natural phenomenon to be studied using "objective" scientific methods and those who believe human behavior could not be understood outside of particular histories, cultural contexts, or subjective understandings. Universalists were more prominent (though not universal) in economics, sociology, and political science at much less dominant in history and anthropology (Wallerstein 2003). This oversimplify