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Science communication across disciplines

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Introduction

Behind the general issues of communicating science to the public at large, there are less obvious issues of communicating science to other scientists, although the challenges involved in each overlap. Indeed, because of the tremendous growth and increasing specialisation of science and its fragmentation into numerous disciplines, subdisciplines, and research fields, professional science communications are generally fully comprehensible only by experts of the same research field. The more distant the research fields are, the bigger are the obstacles of understanding. Although all scientists might share some basic ideas about science, a scientist working in a far removed research field might meet obstacles of understanding about a research paper that are not totally different from the obstacles a well-educated non-scientist encounters.

The difficulties in cross-disciplinary communication result in many issues that are largely different from those associated with the detachment of non-scientists from science, however. Much more than non-scientists, scientists in their professional work depend on the best available knowledge in other fields. Moreover, if two or more scientists from different disciplines want to collaborate on a common project and do not understand each other, the project is unlikely to succeed. Effective cross-disciplinary communication is therefore a precondition for successful interdisciplinary work. Interdisciplinarity has been considered a source of innovation (see Weingart 2000), through cross-fertilisation of disciplinary knowledge, which partly explains why cross-disciplinary communication issues have recently come to the fore. If each discipline or research field develops in isolation, science runs the risk of fragmentation—in stark contrast to the traditional notions of the unity of science. Because of the sheer size of science and the difficulty of effective communication, it has long been impossible to achieve an ‘overview’ of all branches of science. Without such an overview, each field is more likely to go its own way, free of monitoring or control from outside. The risk then is that within each field, experts take it upon themselves to decide on progress, in what are often publicly funded areas of research, because they are the only ones able to fully understand it.

This chapter provides an introduction to issues of cross-disciplinary communication and interdisciplinary research. The section that follows explains how and why these issues have historically emerged since the 19th century. Before addressing these key issues, we first need a better understanding of what disciplines are, how they differ from each other and how to describe their relationships. Because disciplines are both cognitive and social entities, there are cognitive as well as social strategies to improve cross-disciplinary communication, discussed in detail in later sections. Taking nanotechnology as the latest example to establish research across all major science and engineering disciplines, I then critically examine recent political efforts to support an interdisciplinary culture. Finally, I draw some conclusions about the extent to which cross-disciplinary communication can actively be controlled from the outside.

The growth and disciplinary fragmentation of science

As recently as the 18th century, different scientific disciplines in the proper meaning of the term hardly existed. Although different branches of knowledge of the natural world have been distinguished ever since antiquity, a scientist, then still called a natural philosopher, usually worked in many, if not all, areas, mostly as an amateur or member of a scientific society. Communication issues resulted from personal idiosyncrasies rather than from specialisation. Scientific societies cultivated the exchange of ideas across the fields through convening regular meetings and publishing journals that combined all fields of scientific knowledge.

That situation changed drastically in 19th-century Europe, when newly structured universities became the institutions of scientific discipline formation. Formerly institutes of education for theology, medicine and law only, universities upgraded their philosophical or faculties to offer not only undergraduate education but also higher degrees and doctorates in philosophy, which comprised everything we nowadays call natural sciences, social sciences and humanities. In addition, universities, which up until that time were merely educational institutes, established facilities in which professors and graduate students undertook research. The rapidly increasing societal demand for graduates enabled the philosophical faculties to flourish and grow, and to offer more specialized education and degrees. Professors, who formerly taught all kinds of courses, began to focus their teaching activities on fields related to their own research. As they found their own specialisation, they wrote textbooks, started to edit specialized journals and trained graduate students to become professors of the next generation in their specific field. Increasing specialisation thus led to the differentiation of disciplines, which defined and demarcated their own research fields, established communication structures and produced professionals and teaching staff. Simultaneously, the polytechnic schools typical of many European countries, founded in the late 18th and early 19th centuries to educate engineers, flourished and underwent a similar process of specialisation and discipline formation. Here the original scope of mechanical, civil and military engineering was extended both by further specialisation and in response to new industrial development and needs, to include new fields such as chemical and electrical engineering. The process of increasing specialisation and fragmentation of science into disciplines, subdisciplines, and research fields, which started in the 19th century, has continued throughout the 20th century up to the present day.

There are several reasons why science fragmented into increasing numbers of disciplines, subdisciplines, and research fields. Most importantly, science has grown exponentially over the past two centuries, according to any quantitative measure, such as the number of publications, journals, scientists, research institutions, and so on (de Solla Price 1961, 1963). All such numbers have roughly doubled about every 15 years during this period, which corresponds to an annual growth rate of some five percent. It follows that, in order to keep up with the latest research, researchers need to focus on a comparatively small research field. When the field itself grows beyond the reading capacity of a researcher, the split into sub-fields seems unavoidable. Furthermore, science as social activity depends on personal contacts with one's peers, in order to share implicit knowledge that cannot be communicated in written form and to distribute resources and career opportunities. As with any other social group, there is a limit in one's capacity to cultivate personal contacts, which determines the upper size of the group and thus fosters the splitting of the group once the limit is reached. And since the establishment of a new research field has become an important factor for the reputation of a scientist, this has provided further incentives for diversification and fragmentation.

Scientific findings are communicated primarily to peers or colleagues, which serves two main functions essential to modern science. First, results are shared among peers so that they can benefit from the result in their own research and, in return, give public credit to the authors. Second, peers might criticize the result as unsound or correct it in a subsequent publication, which keeps the methodological standard of the profession high and (at least in theory) prevents errors and inconsistencies. Both functions require that the communication is as precise as possible and fully comprehensible to peers. These requirements thus force scientists to formulate their communications according to the standards of their specific research field in a precise technical language, which fundamentally differs from ordinary language and the languages of other fields and disciplines. In other words, modern science requires that professional science communications are less comprehensible by non-scientists and, as science grows overall, by a growing fraction of scientists.

In addition to the long-term trend of the incremental fragmentation of science into specialities, there is a more recent trend over several decades towards increased interdisciplinary research (Gibbons *et al.,* 1994). These two trends need not oppose each other, because interdisciplinary research frequently ends up in a new speciality or even in a new discipline, distinct from the disciplines it came from. The discipline of materials science, which emerged since the 1970s largely from physics and chemistry, is a recent prominent example. However, the trend towards interdisciplinary research is also driven by political and economical factors. Since public funding of research has grown much faster than the gross domestic product in most countries, societies generally require in return that research outputs have greater utility. In this regard, the two trends oppose each other. A new discipline or subdiscipline usually establishes itself by defining its specific research problems and foundations within the academic landscape, so that it is clearly distinguished from the other disciplines. In contrast, usefulness by general societal standards requires that research problems are coordinated across disciplines and geared towards societal needs. Thus, the politically-desirable shift towards interdisciplinarity for the sake of improved usefulness, of which nanotechnology is the latest example, clearly acts against the long-term trend of the disciplinary fragmentation of science. Because fragmentation is a necessary outcome of the growth of science, tensions and issues of interdisciplinary communication are unavoidable, as we will see in the discussion of nanotechnology later in this article.

Disciplines and their relationships

In order to understand cross-disciplinary communication issues and the strategies to address them, we first need to have a better understanding of what disciplines are and how to describe their relations.[1]

The English term 'discipline' (from Latin, *disciplina*) has a complex meaning, as the following sentence illustrates: Students (disciples) learn a certain doctrine (a discipline) by obeying strict (disciplinary) rules of a school (a discipline) and by practicing self-control (discipline). A discipline is not simply an abstract set of information, but both a body of knowledge that is taught at a school and the social context of the school. Disciplinary knowledge requires a social context of transmission and education and a social body that reproduces itself by educating students to become future teachers. A scientific discipline thus comprises both cognitive and social aspects.

The *cognitive aspects* of a discipline refer to a body of knowledge of three kinds: concepts and beliefs, including facts, classifications, models, and theories (knowledge of the word); methods for increasing and validating the knowledge of the world and for problem solving (knowledge of methods); and values for judging the relevance and importance of the knowledge (knowledge of values). Hence, two disciplines differ not only in the specific set of information and concepts about the world, but also in what they consider important research questions, how to approach the problems and how to assess solutions. Cross-disciplinary communication issues thus arise not only because of different terminologies and information about the world, but also because of a different understanding of values and methods.

[1] For more details, see the 'Further reading' section at the end of the chapter, as well as Schummer (2004a) on which this and the following two sections draw.

The *social aspects* of a discipline refer to a social body or a community of scientists who largely share the three kinds of knowledge and who feel committed to the community. The commitment includes active engagement in increasing and improving the disciplinary body of knowledge through research, in communicating it through publications, and in teaching it to students. Like other social groups, a disciplinary community has rules for becoming a junior member (by graduation), for gathering (in society meetings), for distributing honour (through awards and society positions), for reproduction (through teaching appointments), for community-like behaviour (through codes of conduct), and for representing itself to publics. Being a member of a disciplinary community does not per se pose specific cross-disciplinary communication issues. However, the commitment to the community reinforces the cognitive issues and, because groups tend to stick together, it reduces the experience of cross-disciplinary communication (Box 1).

Box 1: Relationships between disciplines

The term *multidisciplinary* describes a loose or additive relation between the disciplines involved. For instance, a journal that compiles papers from many disciplines, like *Science* or *Nature*, is multidisciplinary as long as each paper is written by authors of the same discipline. In contrast, *interdisciplinarity* requires stronger ties, overlap, or interaction between the disciplines involved. For instance, a paper or a research project is interdisciplinary if researchers from different disciplines successfully interact with their different disciplinary knowledge. Sometimes a paper is considered interdisciplinary if it does not exactly fit within a single disciplinary category. However, a discipline is not a static entity but develops flexibly over time—the category might therefore simply be outdated.

Two other terms are sometimes used in the sense of interdisciplinary, but, strictly speaking, they do not describe the relationship between disciplines. The term *cross-disciplinary* describes a move across the boundaries of disciplines, like that of information or communication. *Transdisciplinary*, although still a matter of intense debate, describes a form or state of science in which disciplinary structures, boundaries and commitments no longer exist. The term is frequently used to express political ideas of how science should or will be in the future, although project-based industrial research, which is usually far removed from academic disciplines and teaching, might already come close to that concept at times.

There are various models to describe the dynamics of disciplines and their interaction, but we are far away from a full understanding. For instance, multidisciplinarity can be a preliminary step towards interdisciplinarity, such as when loosely aggregated disciplines begin to interact, but in most cases nothing follows. Similarly, many believe that interdisciplinarity is a preliminary step towards transdisciplinarity, such that all disciplinary boundaries vanish through intense interactions between the disciplines. However, interdisciplinarity can also inspire the mother disciplines to form new subdisciplines that each try to claim the new domain, like physical chemistry and chemical physics, biochemistry and molecular biology, and so on. Or, interdisciplinarity can result in a new discipline that grows independent from the mother disciplines, like materials science that emerged from the interaction between physics and chemistry.

Cognitive strategies for improving cross-disciplinary communication

Following this two-level definition of a discipline, we can distinguish between cognitive and social strategies for improving interdisciplinary communication, although these strategies can of course be interactive.

Cognitive strategies seek to level out the differences in disciplinary knowledge, or at least to enable successful communication despite the differences. Ideally, cross-disciplinary communication requires that scientists from different disciplines share the same knowledge basis—knowledge of the world, knowledge of methods, and knowledge of values. However, as long as there are different disciplines in the proper sense, any common basis of overlap is modest in scale, because disciplines greatly differ in how they describe the world, in their methods for validating knowledge and solving problems and in assessing the quality and importance of pieces of knowledge. There are four cognitive strategies to smooth cross-disciplinary communication, but none of them provides easy solutions.

The most ambitious one is the philosophical idea of the unification of science through *reductionism*. In this approach, all the disciplines need to restructure their disciplinary knowledge such that it is translatable or reducible to some fundamental knowledge—the disciplinary knowledge of physics has generally been considered the ideal candidate. This requires at first that all descriptive knowledge of a discipline, i.e. specific concepts, models and theories, should be translatable into the language and theories of physics. More ambitiously, the methods and values of physics should also become the model for all the other disciplines. Popular as the idea was among 20th-century philosophers of physics, it turned out to be naive because it disregarded the diversity of the cognitive structure of disciplines. However, the approach can smooth cross-disciplinary communication in very specific cases, if one finds a common knowledge basis into which fragments of knowledge from each discipline can be translated.

The second strategy, *simplification*, seeks a common basis in everyday knowledge. Because we share to some extent a common experience through language, a rich source of metaphors and images, and a common-sense understanding of what matters and what is sound, this is a useful point to start with. However, there is a clear risk that over-simplification can create misunderstandings or the false impression of understanding where there is actually none. Oversimplification can also create artificial problems and solutions, suggested for instance by everyday metaphors, that can mislead rather than promote interdisciplinary research. Thus simplification can only be a preliminary step towards developing a more sophisticated form of communication. A second step, which Galison (1997) has found in his analysis of large-scale interdisciplinary research in particle physics, is the development of special jargons or creoles. These are inter-languages that are tailored to the needs of the specific project by combining necessary concepts from different languages and excluding unnecessary concepts that are mutually incompatible or incomprehensible.

A third strategy to smooth cross-disciplinary communication consists of reducing communication to restricted interfaces. *Modularisation* divides up an interdisciplinary project into mono-disciplinary modules, i.e. sub-projects, with well-defined types of information input and output from and to the other sub-projects. However, modularisation works only if the project architecture is simple, such that no disciplinary particularities affect the exchange of information, and if no unforeseen problems arise. Once such problems emerge, the interdisciplinary team may encounter particularly grave communication issues because of their inexperience in dealing with each other beyond the interfaces. Nonetheless, a well-designed organisation of an interdisciplinary project in addition to regular exchanges and flexible arrangements can be a useful measure to avoid unnecessary communication problems.

The fourth strategy, *translation or mediation*, requires a translator who should ideally be educated in all the disciplines involved. Moreover, because there is no simple translation between the knowledge types of all disciplines, the translator needs to mediate not only between different types of description but also between different opinions on what is sound and important and on how to tackle a problem to best effect. Of course this requires sophisticated social and communicative skills, and it allows the mediator to control the project to a considerable degree. Mediation and translation would certainly be the best cognitive solution to cross-disciplinary communication issues, in particular because mediators can additionally educate scientists from different disciplines to understand each other better. However, mediators are rarely available because there is neither a profession nor a specific education for cross-disciplinary mediation, which leads us to social strategies for improving cross-disciplinary communication.

Social strategies for improving cross-disciplinary communication

Social strategies alone cannot directly enable cross-disciplinary communication because they cannot overcome the cognitive gaps between disciplines. However, they can establish social conditions under which mutual learning and understanding are improved and they can weaken the social commitments of scientists to their specific discipline to increase mutual openness.

The most ambitious approach is, of course, the establishment of broad multidisciplinary teaching rather than the monodisciplinary education that is characteristic of modern higher education. This would produce future researchers who have no disciplinary focus and commitment with the potential to freely communicate and collaborate with each other on any project. Yet, since the breadth of education within a limited period is achieved at the expense of depth, it is questionable if such education can qualify for cutting-edge research. We have seen that the fragmentation of knowledge into ever more specialized sub-areas has been driven by the growth of science; it cannot simply be reversed. However, a broad multidisciplinary teaching program could be useful to educate mediators who specialize in smoothing cross-disciplinary communication. If offered to all science students in their first year before disciplinary specialisation, such a program could also provide some basic understanding of other disciplines to improve future cross-disciplinary communication. Furthermore, specific teaching programs that combine two or three disciplines can train students to work in corresponding interdisciplinary projects and settings.

Because education does not end with graduation, there are many opportunities to provide further education in other disciplines than one's own during a scientific career. Apart from formal further education programs, there is a range of multidisciplinary science journals, popular magazines and books. Multidisciplinary journals, like *Science* and *Nature*, highlight important research in all disciplines, and thus provide ideal opportunities to keep up with what is going on beyond one's own discipline. Similarly, review articles summarize important developments and address a general scientific readership. There are also many multidisciplinary journals in specialized fields—sometimes wrongly called interdisciplinary—but which aim to prepare professional readers for interdisciplinary research and communication. Although popular science magazines and books are written primarily for non-scientists, they also attract a wide readership among scientists who seek an easy introduction to fields other than their own.

Apart from education, the social conditions for research can be considerably improved to foster the cross-disciplinary exchange of ideas. For instance, one can weaken the bureaucratic boundaries established between disciplinary departments, each with their own decision-making processes, budgets for research equipment, personnel, library, colloquia, and so on. More ambitiously, a suitable architecture can make researchers from different disciplines close neighbours with formal and informal exchange on a regular basis rather than inhabitants of separate department buildings. From informal networks and consortia to inter-departmental research groups and centres with budgets and administration, research institutions can not only aim at interdisciplinary research results, they also provide the social setting to facilitate and fashion cross-disciplinary communication. Finally, because money is always a powerful incentive, research grants that require interdisciplinary collaboration can help bring scientists from different disciplines together who would otherwise lack the opportunity to do so. On the bureaucratic side, this in turn requires that research funding agencies are not divided according to disciplinary lines.

All social strategies for improving cross-disciplinary communication and interdisciplinary research to some degree weaken the disciplinary identity and commitments of researchers. From a sociological point of view, it is questionable if these group identities can be totally dissolved without substitution. On the other hand, establishing a new group identity can be a powerful strategy to abandon former allegiances. In order to replace a disciplinary group identity, one needs more than just a strong commitment to, say, a local research centre, because the new group identity needs to be established on a par at least equivalent with the previous entity. Thus, the more powerful the establishment of a new group identity is, the more it employs the usual elements of discipline formation, which includes the establishment of all the cognitive and social components of a discipline already discussed. Furthermore, to make a new interdisciplinary field attractive, it needs to be popularised as particularly important, worthwhile enough to invest money in, and capable of starting research careers. Typically propagators of new a field write histories which define the founders in order to shape its identity and these generally refer to early and widely accepted authorities in order to add seriousness and attractiveness to the field.[2] Such histories provide a dynamic view of the field by placing current activities into the overall historical development and by providing extrapolations from the past to the future in the form of future visions. Expressed in simple terms with reference to general human needs, such visions provide quick answers to why-questions, which researchers in highly specialized fields often have difficulty answering. By sharing the same visions and history, researchers originating from different fields can readily find a new common group identity.

The more powerful social strategies for improving cross-disciplinary communication are, the more they employ the classical elements of discipline formation. Of course, that runs the risk of resulting in a new discipline, which later inherits the same problems of cross-disciplinary communication. On the other hand, the weaker the strategies, the more likely are their effects to be no more than superficial and temporary.

The example of nanotechnology

Nanotechnology is the latest political effort to establish interdisciplinary research on a large scale, spanning all the established major science and engineering disciplines and acting in opposition to the long-term trend of disciplinary fragmentation. The potential practical applications of nanotechnology are considered enormous, as is its commercial significance. From about 2000, in all industrialised and many developing countries, huge national research programmes have been launched, making it an ideal field to study issues of interdisciplinary research and cross-disciplinary communication.

Nanotechnology is not simply a new specialized research field as the term might suggest. In fact, all definitions of nanotechnology are very vague. For instance, a widely used definition defines nanotechnology as the study of material structures in the scale of 1-100 nanometres (a nanometre being a billionth of a meter), in order to discover and exploit new properties of materials and devices that depend on nanoscale structures for useful applications. Indeed, almost all materials are structured in the nanoscale in such a way that the structure determines their properties. Chemistry has, at least since the mid-19th century, always complied with that definition, as for many decades have molecular biology, pharmacology, solid state physics,

[2] Examples include Joseph Priestley's history of electricity from 1767, Wilhelm Ostwald's history of electrochemistry from 1896, and the historiographical and autobiographical efforts by James Watson in the 1960s to shape molecular biology (Abir-Am, 1999).

materials science and engineering, as well as larger branches of electrical, chemical, and mechanical engineering and so on. While such vague definitions might be unsatisfactory from an academic point of view, in practice they allow the integration of many disciplinary research activities under the new umbrella of nanotechnology.

While the individual research activities that are nowadays called nanotechnology originate from many previous mono- and interdisciplinary research traditions, the umbrella concept of nanotechnology is a political idea. More specifically this idea was developed in the USA in the late 1990s—in part as a response to the 'Atom Technology Project' that the Japanese government operated at its research institutes since 1993—and resulted in the launch of the US National Nanotechnology Initiative (NNI) in 2000. Because the NNI has been widely copied by other countries since then and is well documented, the following analysis focuses on the NNI and its impacts and discusses other countries only insofar as they substantially differ.

Science policy-makers have limited capacities to directly improve interdisciplinary research and cross-disciplinary communication, because their efforts are largely confined to social strategies, and in this example especially to funding. Lacking any direct impact on the cognitive structure of science, they can use only the power of words to convince scientists of the attractiveness, usefulness or necessity of cognitive integration. In this regard, the NNI started with the powerful idea of a revolution in science according to which the long-term fragmentation of disciplines would suddenly reverse towards a new convergence at the nanoscale. As the architect of the NNI, Mihail Roco, put it:

> A revolution is occurring in science and technology. … At the nanoscale, physics, chemistry, biology, materials science, and engineering converge toward the same principles and tools. As a result, progress in nanoscience will have very far-reaching impact. (Roco and Bainbridge 2001, p. 1)

One might easily dismiss such a statement as naive confusion of facts and wishes (Schummer 2008). However, it expresses the somewhat helpless vision of vanishing cognitive barriers between the disciplines (here, on the level of principles and methods), put forward in the hope that scientists might feel inspired to actually realize that vision. By combining the cognitive strategies of reductionism and simplification, the NNI and its forerunner organisation promoted the idea that the world consists of simple Lego-like building blocks that can easily be imaged and rearranged (NSTC 1999). Once all disciplines agree on these building blocks, they would collaborate on rebuilding the world according to societal needs.

Strong efforts have been made to develop visions of a promising nanotechnology future to convince scientists of a common value basis that should both direct their collaborative research on the cognitive level and form a new group identity on the social level. In particular, the NNI, at least at the beginning, employed parts of Drexler’s (1987) futuristic vision of 'molecular nanotechnology'; to bring unprecedented wealth, health, and security through the development of robots on the molecular scale. They soon extended the scope of disciplines to also include computer, cognitive and some social sciences, all converging with nanotechnology in what has been called 'converging technologies', for the ultimate goal of enhancing physical, mental and social capacities of humans (Roco and Bainbridge 2002). In addition to visions, the popularisation of nanotechnology also comes with a standard history in which the US Nobel Prize winner Richard Feynman is posthumously made the founder of nanotechnology and an illustrious list of other Nobel laureates are described as early nanotechnologists.

Apart from the power of words, the NNI has distributed billions of dollars to support interdisciplinary research. The primary means has been the funding of interdisciplinary research projects and, particularly, centres at universities for a limited period, 'to provide strong support for the development of an interdisciplinary culture', as the reviewers of the NNI required (NRC, 2002, p. 3). In addition, as an inter-agency institution, the NNI undermines the bureaucratic division of research funding agencies along outdated disciplinary lines, such as that between the National Science Foundation (NSF), which is responsible for physical sciences and engineering plus some chemistry, and the National Institute of Health (NIH), which supports biomedical sciences and engineering plus some chemistry.

Compared to these strong efforts at developing an interdisciplinary research culture, the NNI and its sister initiatives in other countries have largely neglected education, the most promising social strategy for improving cross-disciplinary communication. For instance, in the US the institutional support for developing interdisciplinary education started only in late 2004 with the establishment of a National Center for Learning and Teaching in Nanoscale Science and Engineering (NCLT) that is modestly funded with less than 0.3 percent of the NNI budget.

Fostered by nanotechnology research programs worldwide, the global institutionalisation of nanotechnology has gained an unprecedented momentum with annual growth rates of more than 50 per cent, such that after only a few years most major universities have at least one interdisciplinary nanotechnology centre or group (Schummer 2007). Since about 2004, a rapidly increasing number of universities also offer undergraduate or graduate programs in nanotechnology—particular in Europe, as a side-effect of the ongoing university reform that aims to make higher education compatible among European Union member states ('Bologna Process'), and in fast developing countries such as China and South Korea, because new educational institutes and programs are established according to current needs rather than to past models. In addition learned societies, and more recently commercial publishers, have launched more than two dozen nanotechnology journals by 2006, which are all intended to be interdisciplinary.

Whether the political impetus to create an interdisciplinary culture that smoothes cross-disciplinary communication is actually successful or not remains to be seen. In many regards, nanotechnology is still a loose multidisciplinary aggregation rather than interdisciplinary. Many of the supposedly interdisciplinary journals are still predominantly monodisciplinary, reflecting their allegiance to their publishers, like *Nano Letters* (published by the American Chemical Society), *Nanotechnology* (Institute of Physics) and *Transactions on Nanotechnology* (Institute of Electrical and Electronics Engineers). Beneath the surface, each classical discipline cultivates its own brand of nanotechnology, hence claiming a share in the huge budgets—and often demonstrating an affiliation to nanotechnology by adding the nano-label to ongoing research. Even if the journals are multidisciplinary, their individual papers are mostly written by authors from the same discipline (Schummer 2004b). A critical survey of 35 educational programs in nanotechnology in North America, Europe and Australia has found that the vast majority of the programs are monodisciplinary rather than interdisciplinary and that the nano-label is largely chosen to attract students to what are in effect traditional programs (Brune *et al.,* 2006).

Moreover, the fast institutionalization of nanotechnology research at universities does not necessarily result in a lasting interdisciplinary research culture. While the forms of institutionalization greatly differ from country to country, there seem to be two prevailing models, the 'temporary centre model' and the 'disciplinary model' (Schummer 2007).[3] Interdisciplinary centres, networks and consortia are temporary associations between researchers from different disciplines based on common interests. Because such associations are frequently decentral-

[3] Among all countries Japan stands out because it has institutionalized nanotechnology largely at governmental research institutes through five- and ten-year plans rather than fostering the academic institutionalization at universities. As a result the relative global institutionalization strength of Japan dropped from about 37% in 1997 to some 7% in 2006 (Schummer 2007).

ized institutions established for the acquisition of funding, it is uncertain if they actually foster interdisciplinary research and cross-disciplinary communication and if they continue to exist once the funding ends. In contrast an interdisciplinary group consists of researchers from one or more disciplines who work on an interdisciplinary research project. If the group grows, it may upgrade to a department or school, which is more permanently integrated into the disciplinary structure of the university, and thus becomes the kernel of the formation of a new discipline. Through the funding policy of the NNI, the US has a clear focus on the temporary centre model, whereas many European and Asian universities have already established nanotechnology at the department level and thus follow the disciplinary model. In both cases, however, interdisciplinarity may well prove little more than temporary. The political efforts at cultivating interdisciplinarity thus navigate between the Scylla of a loose temporary aggregation and the Charybdis of a new discipline.

Given the complexity of the issue and the variety of cognitive and social strategies, the political efforts thus far appear to be very limited, short-sighted, and sometimes naive. The focus on funding is crippled by the short-term commitment of governments, such that nanotechnology might drop from the science policy agenda as suddenly as it appeared, whilst the most promising, albeit long-term strategy of multidisciplinary education has hardly been tried; the same holds for cross-disciplinary mediation (for an exception, see Gorman *et al.,* 2004). The substantial cognitive barriers between disciplines have been totally ignored or downplayed by propagating a simplistic Lego-like worldview that is hardly likely to convince established researchers (Schummer 2004a). And while the exaggerated visions may have generated some public concern, they have generally caused scepticism and divisions among some scientists. On the whole this suggests that nanotechnology might turn out to be a missed opportunity for improving cross-disciplinary communication.

Conclusion

The case of nanotechnology is instructive because it illustrates the complexity of interdisciplinarity and the problems of political control. Disciplines are both cognitive and social entities with their own dynamics of growth, change, fragmentation and mutual exchange. Substantial changes are measured in decades rather than in years and need to be supported by large sections of the scientific community rather than just imposed from the outside—otherwise the system reacts with pseudo-changes such as relabeling research to please science policy makers. Because education is the very core of disciplines, any effective measure to control disciplinary dynamics and improve cross-disciplinary communication needs to start with education, which requires both willing scientists as teachers and patience to wait for the next generation. Although cross-disciplinary communication is a much desired goal, the sheer size and continuous growth of science requires that this can only be achieved either on a very general level or, if more detailed, for very specific interdisciplinary fields. However, if they find appropriate roles in research institutions, both generalists and interdisciplinary specialists can ease many important cross-disciplinary communication issues through mediation, organisation and participation in research.

It would be naive to consider disciplines themselves simply as an obstacle to cross-disciplinary communication, such that if they disappeared, communication would flow without boundaries. Disciplines are essential for education, for structuring knowledge and for controlling the internal quality of science; and they form the social dimensions of science that bear many of the characteristics of ordinary social life. As long as we have no fully functional substitutes for that, abolishing disciplines for the sake of cross-disciplinary communication would be throwing out the baby with the bathwater.

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Schummer, J. (2008, forthcoming). From nano-convergence to NBIC-convergence, in S. Maasen, M. Kaiser, M. Kurath and C. Rehmann-Sutter (eds.) *deliberating future technologies: Identity, ethics, and governance of nanotechnology*. (Springer: Berlin and Heidelberg.

Weingart, P. (2000). Interdisciplinarity: The paradoxical discourse, in P. Weingart and N. Stehr (eds.) *Practising interdisciplinarity*. (University of Toronto Press: Toronto).

Further Reading

Klein, J.T. (1990). *Interdisciplinarity: History, theory, and practice*. (Wayne State University Press: Detroit).

This is a classic, and still the best, introduction to the concept of interdisciplinarity with a huge bibliography. More detailed and more recent books on interdisciplinarity by the same author include *Crossing boundaries* (University Press of Virginia, 1996) and *Humanities, culture and interdisciplinarity* (State University of New York Press, 2005).

Kline, St. J. (1995). *Conceptual foundations for multidisciplinary thinking*. (Stanford University Press, Stanford, CA).

This book analyses methodological and conceptual issues of interdisciplinarity from a systems theory approach. The fourth part of the book, where the author analyses various fallacies in creating interdisciplinarity, is particularly useful.

Weingart, P. and Stehr, N. (eds.) (2000). *Practising interdisciplinarity*. (University of Toronto Press: Toronto).

This anthology investigates the recent shift towards interdisciplinarity from a science studies perspective. The theoretical analyses are complemented by many useful case studies on the actual practice of interdisciplinary research centres and funding institutions worldwide.

Schummer, J. and Baird, D. (eds.) (2006). *Nanotechnology challenges: Implications for philosophy, ethics and society*. (World Scientific Publishing: Singapore).

This volume—written by philosophers, historians and sociologists of science—provides an introduction to the recent emergence of nanotechnology across the disciplines and its various philosophical, ethical and societal issues.

Useful websites

US National Nanotechnology Initiative (NNI): http://www.nano.gov

Under 'Resources/Publications' this websites provides useful and detailed documentation of the US Nanotechnology Initiative since 1999.

Nanoforum: http://www.nanoforum.org

The UK-based website provides the most comprehensive information on EU activities in nanotechnology. For full access to all sources, free registration is required.

Nanotechnology Now: http://www.nanotech-now.com

Among the numerous nanotechnology news portals, this is probably the most comprehensive one, with the typical mixture of research, business and visionary enthusiasm.

Rethinking Interdisciplinarity: http://www.interdisciplines.org/interdisciplinarity

The French project 'Interdisciplines' has organized a number of international online conferences and seminars, including one on Rethinking Interdisciplinarity in 2003/2004 with full papers available.

Bibliography on Interdisciplinarity:
http://www.grad.washington.edu/Acad/interdisc_network/ID_Docs/bibliography_Interdisc.pdf

Although a bit outdated (2003), this is the best available online bibliography on interdisciplinarity compiled by Gail Lee Dubrow from the University of Washington.