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Interdisciplinary Issues in Nanoscale Research

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Abstract. Great expectations and promises rest on interdisciplinarity in nanoscale research. Yet, although many science and engineering disciplines actually began to engage in this field, it is only poorly understood what interdisciplinarity actually is and what factors hinder and promote it. Part I provides an introduction to interdisciplinarity, its cognitive and social elements, and its related concepts, such as multi- and transdisciplinary or super-interdisciplinary. Part II first presents empirical findings about the actual weakness of interdisciplinarity in current nanoscale research and then discusses two of the main conceptual reasons for this. I argue that definitions of nanoscale research are too vague to provide interdisciplinary integration and that current nanotechnological visions include discipline-rooted and metaphysically opposed technological paradigms, such as 'self-assembly' vs. 'atom-by-atom-manipulation', that pose strong barriers to interdisciplinary research.

Introduction

Nanoscale research is currently attracting tremendous attention from both the general public (Schummer 2005) and from a large variety of science and engineering disciplines (Schummer 2004). The attraction is largely fostered by technological visions, the promises of new scientific discoveries, and huge governmental funds. Such a melting pot of various disciplines promises to be a great opportunity for innovative research through synergetic effects, provided that researchers from different disciplines find a common basis required for interdisciplinary research. If that is missing, however, disintegration is to be expected and researchers will at best do their disciplinary research business as usual, though under a new label. Therefore, the understanding and mediating of interdisciplinarity is a crucial factor in the future success of nanoscale research. Yet, although every report on nanoscale research highlights the necessity of interdisciplinarity,[1] little effort at understanding interdisciplinarity has been made. To the contrary, there is currently a naive rush from badly understood interdisciplinarity towards new visions of super-interdisciplinarity to be centered on nanotechnology (Roco & Bainbridge 2002).

A sort of longish introduction, the first part of this paper presents some general ideas about interdisciplinarity and its related concepts, such as discipline, multi- and transdisciplinary or super-interdisciplinary. The second part starts with a summary of scientometric findings about multi- and interdisciplinarity in current nanoscale research (Schummer 2004). Since these findings suggest that interdisciplinary nanoscale research is indeed in a bad shape, the rest of the paper analyzes two specific reasons for this. On the one hand, I argue that current definitions of nanoscale research, which are mainly based on the size of objects, are too vague to provide any integrative function. On the other hand, I point out that certain discipline-rooted technological paradigms, such as 'self-assembly' and 'atom-by-atom-manipulation', which are currently employed in nanotechnological visions, are barriers to interdisciplinarity insofar as they include metaphysical oppositions that disintegrate rather than integrate the disciplines.

1. Elements of Interdisciplinarity

1.1 A Brief Survey of the Literature

Strangely enough, the literature on interdisciplinarity is multidisciplinary rather than interdisciplinary (for the distinction, see below). It includes scholars from science education, sociology of science, history of science, and philosophy of science.[2]

As we shall see, 'discipline' has strong educational connotations. A great part of the literature on interdisciplinarity therefore belongs to professional education and arose from debates about reforms of tertiary education to be based on a broadened scope of general knowledge, like a *studium generale*.[3] Other literature stems from sociology of science and science policy studies. Not surprisingly, scholars in these fields focus on sociological and organizational aspect of interdisciplinarity while neglecting to some extent the cognitive side. Much more integrative perspectives can be found in the numerous detailed case studies of interdisciplinary research and discipline formation by historians of science.[4]

When sociology and history of science merge, this frequently results in 'Big Philosophical Pictures'. A favorite topic is the allegedly new or hoped-for interdisciplinarity between science and technology in problem-based research, for which historical claims have been made and new terms introduced, like 'Technoscience', 'Mode 2 of Knowledge Production'. Such approaches may belong to philosophy insofar as they engage in metaphysical and epistemological debates about modernism/postmodernism or realism/constructivism rather than the historiography of science. In fact, they, more or less explicitly, oppose the other Big Philosophy Picture of interdisciplinarity, the ambitious Unity of Science Project launched by Logical Positivists in the 1930s. Claiming that the disciplinary languages of all sciences can and should be based on or reduced to the language of physics, the Unity project reduced interdisciplinary relations to the reduction of all sciences to physics. With their bias towards physics, modern philosophers of science (or rather, of physics) favored physicalistic reductionism as the only interdisciplinarity relation, be it on the level of descriptive language, theories, so-called meta-theories, ontologies, or methods.[5]

It might be recalled, however, that the cognitive relations between the sciences, or more generally the structure of our overall knowledge, has been a central topic of philosophy ever since at least Aristotle. Behind that stands the classical idea that the ideal structure of our knowledge does or should correspond to the structure of our world – a position that has frequently recurred as either epistemological realism or metaphysical idealism. By emphasizing the impact of social dynamics on the structure of our knowledge, social constructivists could easily challenge the classical idea, particularly in its epistemological variant, with case studies on the social dynamics of the disciplinary structure, provided that the disciplinary structure determines the structure of knowledge. This has made interdisciplinarity a hot topic, although full of ambiguity as to whether 'discipline' is considered a cognitive or a social category and as to whether epistemological claims are meant to be descriptive or normative.

1.2 What is a Discipline?

In its original Latin meaning, which is still preserved in current English as well as in other European languages, the term 'discipline' (from Latin, '*disciplina*') refers to a body of knowledge that is taught in a certain school. Students (disciples) learn a certain doctrine (a discipline) by obeying strict (disciplinary) rules of a school (discipline) and by practicing self-control (discipline). There is no disciplinary knowledge without a social context of transmission and education and a social body that thereby reproduces itself. Modern scientific disciplines do not differ much from that, except that they do not simply preserve but increase and modify a body of knowledge through scientific research – which requires even stricter methodological rules to preserve the continuity of the social body. Thus, a scientific discipline, as I will use the term in the following, comprises both cognitive and social aspects: (1) a body of knowledge, including concepts and beliefs (knowledge of objects), methods for increasing and securing knowledge (knowledge of methods), and values about judging the quality and importance of knowledge (knowledge of values); (2) a social body with effective rules and means for increasing, communicating, and teaching the body of knowledge as a way of self-reproduction.

1.3 Multi-, Inter-, Transdisciplinary, and Super-interdisciplinary

The terms ‘multidisciplinary’, ‘interdisciplinary’, and ‘transdisciplinary’ have been used to describe research activities, research problems, research institutions, teaching, or a body of knowledge, each with an input from at least two scientific disciplines. Although confusion still abounds, there is some agreement that ‘multidisciplinary’ describes a rather loose, additive, or preliminary relation between the disciplines involved, whereas ‘interdisciplinary’ requires stronger ties, overlap, or integration. In some diachronic models, multidisciplinarity is a preliminary step toward interdisciplinarity, which can go as far as to either unify two or more disciplines or to create a new ‘interdisciplinary’ (hybrid) discipline at the interface of the mother disciplines. Transdisciplinarity is a diachronic (if not a political or ‘antidisciplinary’) concept to describe a state of research or knowledge that transcends disciplinary boundaries, with continuous input from various disciplines but without any inclination to consolidate into a new (hybrid) discipline. On the opposite side of this is ‘super-interdisciplinarity’, a term used to describe a new unity of all or at least of many sciences.

1.4 Cognitive Elements and Strategies of Interdisciplinarity

Cognitive elements of interdisciplinarity follow from our definition of a discipline. People from different disciplines involved in a common interdisciplinary research project must share a common knowledge basis, consisting of knowledge of objects, methods, and values. As long as there are different disciplines in the proper sense, the common basis can only consist in more or less overlap, because disciplines greatly differ in their knowledge of objects, in their methods for increasing and securing knowledge, and in their values about judging the quality and importance of pieces of knowledge. There are three approaches to increase overlap.

(1) *Reductionism* tends to ignore the differences of knowledge bodies by inventing hierarchies, such that the knowledge on one level can be reduced to the knowledge on a more basic level. The price of reductionism, which has been favored by many philosophers of science (of physics), is that their picture of scientific knowledge has lost any descriptive value with regard to the actual sciences other than physics.

(2) *Simplification* is a strategy that largely relies on the common ground of everyday knowledge. Because we share to some extent a common experience, an ordinary language, a rich source of common metaphors and pictures, this is a useful point to start with. Since ordinary knowledge does not capture the sophisticated structures of disciplinary knowledge, crude over-simplifications and particular efforts at using visual forms of communication are typical approaches that are all too apparent in current nanotechnology. The risk of simplification is that people stick to artificial problems and solutions, created from oversimplification, and that they do not recognize that simplification can only be a preliminary step towards serious research.

(3) *Translation or Mediation* requires a translator who should ideally be educated in all the disciplines involved. This would certainly be the best solution if mediators were available and socially accepted, neither of which is the case. Alternatively, scientific education could provide a broad scope of multidisciplinary teaching to students, such that everybody involved in interdisciplinary research has at least a basic understanding of the other disciplines. However, the general trend of tertiary education is heading in the opposite direction, which leads us to social elements of interdisciplinarity.

1.5 Social Elements of Interdisciplinarity

Long before the formation of a new discipline comes the step from multi- to true interdisciplinarity. It requires a considerable effort of social integration that involves new infrastructures for communication, collaborative research, publication, and teaching. While these aspects have been dealt with at length in the sociology and science policy literature, I would like to point out two further interrelated factors of social integration that are frequently overlooked because they appear to be only about cognitive integration. Both play a growing role in current nanoscale research; they are the historiography of the field and its visions. As they look into the past and into the future, both frequently appear in the same sort of texts authored by leaders in the field, namely in introductory, review, and editorial essays.

By identifying the founders and heroes of a field, both the field and the community are shaped, if not created.[6] In addition, references to early and widely accepted authorities add seriousness and attractiveness to the field. A powerful tool of discipline formation, self-historiography frequently appears at the earliest state when research is just at the beginning. Two famous historical examples are Priestley's history of electricity from as early as 1767 and Ostwald's history of electrochemistry from 1896. Moreover, historiography takes a dynamic view of the field. It first places current activities into the overall historical development, and thereby provides historical meaning, significance, and links to the current works of researchers. Secondly, it calls for, or is even recruited for, extrapolation to the future, thereby giving plausibility to visions as the natural outcome of the historical development. That is why historiography and the formulation of visions frequently appear closely together.

Visions add further meaning, orientation, and links to particular research projects. Expressed in simple terms with reference to general human needs, visions provide quick answers to why-questions of a general audience – questions which researchers in highly specialized fields have difficulties to answer otherwise. By sharing the same visions, researchers of different fields can see each other as working on the same project or even belonging to the same community. This is the positive aspect of the current production of nanotech visions. Later we will see that visions can also pose barriers to interdisciplinarity.

2. The Bases of Interdisciplinarity in Current Nanoscale Research

In this part, I first present some scientometric results about the disciplinary structure of current nanoscale research and then discuss two elements on which expectations of successful interdisciplinary research largely seem to be based: the length scale of objects and technological visions about future success. The idea behind that seems to be straightforward: in order to integrate a bunch of scientific and engineering disciplines into one project, they must first study the same objects and secondly have the same vision of what the research should aim at technologically – interdisciplinary collaboration will then follow automatically. We will see that this is not that easy.

2.1 Multidisciplinarity and Interdisciplinarity in Nanoscale Research Journals

The journals in which nanoscale research is published are a good source to analyze its multi- and interdisciplinary structure. Although much of nanoscale research is still published in classical disciplinary journals, there are already eight journals devoted to the new field.[7] In the following, I will focus on two journals: *Nanotechnology,* published since 1990 by the UK based Institute of Physics, with 150 regular papers in 2002; and *Nano Letters*, published since 2001 by the American Chemical Society, with 281 papers in 2002. Both journals define their field quite similarly as nanoscience and nanotechnology, and both have an explicit interdisciplinary mission ventilated in their Aims-and-Scope sections.

If one looks at the disciplinary affiliation of the authors, as I have done with 100 papers of each journal (see Figure 1), the combined results present a rich spectrum of all the disciplines involved in nanoscale research, *i.e.*, physics, chemistry, materials sciences, electrical engineering, chemical engineering, and so on. In contrast, in a typical disciplinary journal, *e.g.* the *Journal of the American Chemical Society* (JACS), about 80% of the authors are from the 'mother discipline', with some 20% from neighboring disciplines. From that we may conclude that nanoscale research is in fact multidisciplinary.

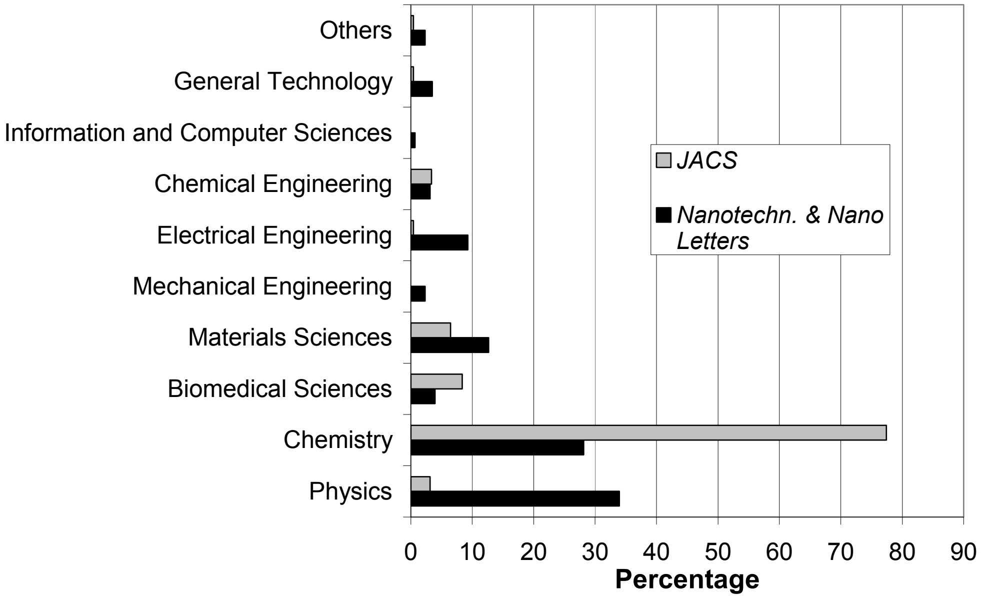

Figure 1. Disciplinary affiliation of authors publishing in 'nano journals' (*Nanotechnology* and *Nano Letters*) as opposed to the disciplinary *Journal of the American Chemical Society* (JACS) (data from Schummer 2004).

Yet, the disciplinary landscape becomes more divided when we analyze each of the two journals separately (see Figure 2). It turns out that we have a 'nanophysics' journal with almost half of the authors from physics; and a 'nanochemistry' journal with almost half of the authors from chemistry. Also, both journals show some preferences for favorite 'guest disciplines' – particularly the physics journal for electrical engineering and chemistry, and the chemistry journal for physics and materials sciences. Still, the overall picture of each journal is more multidisciplinary than disciplinary journals like JACS.

However, a multidisciplinary journal does not necessarily contain interdisciplinary research, since each discipline could publish its papers separately. Interdisciplinary research requires that scholars from different disciplines collaborate to become co-authors of one paper. On average, a paper in nanoscale research has 4.5 authors from 2-3 different institutions; in this regard, it does not much differ from a typical disciplinary journal like JACS.

The question is if the different institutions belong to different disciplines, instead of being located just in different cities. A simple measure for interdisciplinarity of a journal is the number of papers with authors from more than one discipline, the *interdisciplinarity rate* (see Table 1). The surprising result here is that our nanoscale research journals, though being more multidisciplinary, are hardly more interdisciplinary than a typical disciplinary journal like JACS.

I will now discuss two possible reasons why multidisciplinarity of nanoscale research does not lead towards interdisciplinarity.

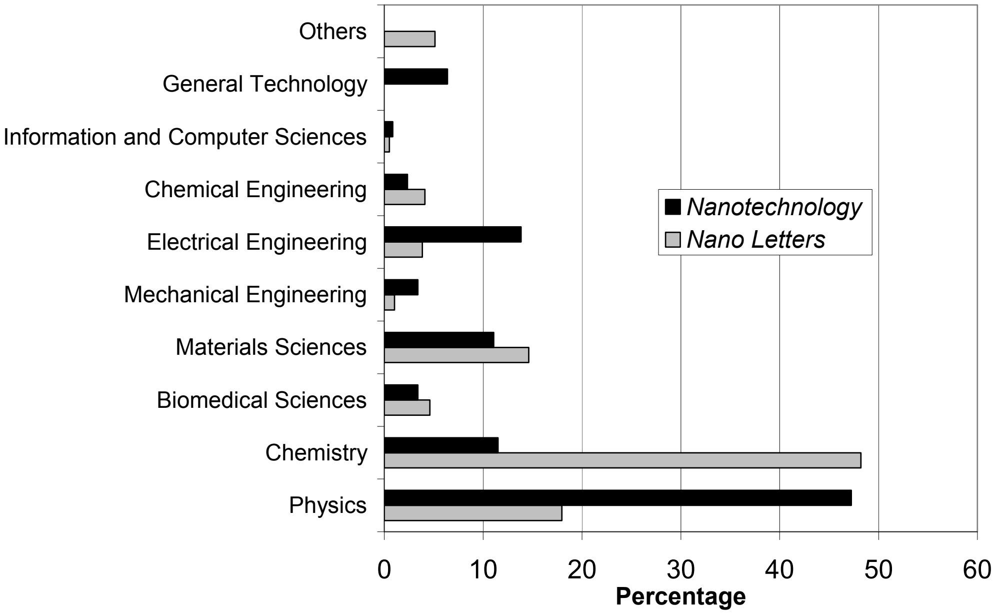

Figure 2. Disciplinary affiliation of authors publishing in *Nanotechnology* and in *Nano Letters* (data from Schummer 2004).

Table 1. Interdisciplinarity rates and main bi-disciplinary collaboration

Journals	Interdisciplinarity rate (%)	Main bi-disciplinary collaboration
Nanotechnology	37	Physics & Chemistry (6%)
Nano Letters	37	Chemistry & Physics (12%)
JACS	30	Chemistry & Materials Science (9%) Chemistry & Biomedical Sciences (9%)

2.2 The Scale of Objects as a Common Basis

Definitions of nanoscale research define this field almost tautologically by the nanometer size of its objects. For instance, the US committee on Nanoscale Science, Engineering and Technology (NSET) defines nanotechnology as:[8]

> Research and technology development at the atomic, molecular or macromolecular levels, in the length scale of approximately 1-100 nanometer range, to provide a fundamental understanding of phenomena and materials at the nanoscale and to create and use structures, devices and systems that have novel properties and functions because of their small and/or intermediate size.

Since that is a precise length range, one might think that the definition of research objects is sufficiently clear. However, while it clearly defines a field of optical research, *i.e.* electromagnetic waves from far UV to soft X-ray, it is difficult to find any kind of matter that would not qualify as an object of such nanoscale research. The only candidates that come to mind are the small molecules and simple ideal crystals that fill introductory textbooks of chemistry – but even those have critical nanometer lengths in the gas phase at appropriate pressures, for example the mean free path length. Nowadays chemists produce more than fifteen million new substances per year, of which virtually all have molecular or crystallographic lengths larger than 1 nm.[9]

Table 2. Examples of commonly known substances with crystallographic lengths in the nanometer scale (data from http://www.reciprocalnet.org)

Substance Name	Empirical Formula	Biggest crystallographic unit cell length
Formic acid	CH_2O_2	1.02410 nm
Buckminsterfullerene	C_{60}	1.40410 nm
Glucose	$C_6H_{12}O_6$	1.48400 nm
Gypsum	H_4CaO_6S	1.52010 nm
Vitamin C	$C_6H_8O_6$	1.71000 nm
Alanine	$C_3H_8ClNO_2$	1.75900 nm
Sulfur	S_8	2.43360 nm
Vanillin	$C_8H_8O_3$	2.50990 nm
Cholesterol	$C_{27}H_{46}O_1$	3.42090 nm
Vitamin D3	$C_{27}H_{44}O$	3.57160 nm
Pepsin		29.01000 nm

Against the rhetoric of novelty, Table 2 provides a few examples of commonly known substances with crystallographic lengths in the 1-30 nm range. The celebrated 'nano-substance' buckminsterfullerene is only slightly bigger than the simplest organic acid, formic acid, and smaller than everyday substances like sugar (glucose), gypsum, or vitamin C, which has long been produced at large industrial scale. Even elements, such as sulfur, arsenic, antimony, and bismuth, crystallize with characteristic lengths in the nanometer scale. Typical substances of 20th-century organic chemistry, here exemplified by the flavor vanillin, the steroid cholesterol, and vitamin D3, are in the range of 2-4 nm. Depending on the number and constitution of their 'building blocks', amino acids, proteins cover a large range of lengths. Simple amino acids, such as alanine, already crystallize with lengths in the 1-2 nm range. The small-to-medium-sized protein pepsin, first isolated by Theodor Schwann in 1836, is almost 30 nm large.

Besides chemistry, almost every other branch of the experimental sciences and technologies deals with material objects structured at the nanoscale. Since it applies ubiquitously, the nanometer scale is insufficient to define any particular or new kind of research.

There is a popular view of the sciences, according to which a hierarchy of material objects is mirrored by a hierarchy of the disciplines: the basic science (called physics) deals with the smallest objects, elementary particles or atoms, that are the building blocks of the objects of the next level, namely molecules which define the field of chemistry. Next comes biology that deals with living beings that are made up of molecules, and finally, if you wish, sociology. Not surprisingly, that originally pre-modern view found expression in the 19th century, when the rapid formation and differentiation of scientific disciplines broke up old dreams of the unity of science. No doubt, creating a new unity of the sciences by conceiving a division of labor according to the scale of their objects served as a sedative for those who wished to hold on to such unity. However, this never had the slightest basis in the actual practice of the sciences. All of our sciences deal or could deal with objects of all length scales, ranging at least from picometers to meters. All combine various micro- and macro-perspectives, and sometimes, as in bulk properties of substances, the size of objects does not even matter.

Regarding the issue of interdisciplinarity, the good news is that, unlike the pre-modern view of science, different disciplines can and do share research objects of the same size – indeed almost every interdisciplinary research is based on sharing the same objects. The bad news is, however, that the lengths scale of objects has never been the main criterion to define a research field; that the nanometer scale is anything else than new, as the phrase 'intermediate size' suggests; and that a shared scale of objects is hardly sufficient to integrate different disciplinary perspectives.

Give a macroscopic object, say an old coin, for professional investigation to a chemist, an economist, and a historian, and you will hardly notice that they speak about the same object. This is even worse with objects beyond human perception, because here our common ordinary life practices of characterizing and referring to objects fail. In the molecular world, we need sophisticated instruments for characterization. And instead of pointing to an object of common reference, it is symbolic, theory-derived representations to which we must at first refer in scientific communication. If a chemist, a biologist, and a physicist talk about a certain kind of molecule, they may have some idea of sharing a common object because they have shared some basic education at school. Yet, as professionals, each has a different understanding of what a molecule is and what its essential features are. The chemist might analyze the molecule in terms of functional groups or reactivity sites, the biologist might be looking for biological information or biological functionality, whereas the physicists could be interested in spatial structure or electromagnetic properties.

One need not be a constructivist to accept that the scientific objects of different disciplines considerably differ from each other because each discipline has another cognitive, instrumental, and problem perspective on objects. As a realist one can claim that all perspectives can be focused on the same 'bare object' – yet what matters in science are not 'bare objects', nor the notorious Building Blocks of Everything, but scientific objects that considerably differ from discipline to discipline.

One might object that I have stuck to conventional science and ignored the important new features that appear at the so-called 'threshold' of the nanoscale and which deserve to create a new research field on its own. After all, by varying the size of material objects at the nanoscale, we can tune many properties that depend on the electronic structure at the objects' surface, like electromagnetic or catalytic properties. And by furthering supramolecular chemistry or by modifying the basic systems of genetic engineering, we could create new machine-like devices with new functionalities. That is all true, and promising indeed. However, just as the understanding of what a molecule is differs considerably between chemists, biologists, and physicists, so does their understanding of what a larger nanoscale object is. The size of objects simply does not matter. It is their disciplinary perspective that render their objects different from or similar to each other, as a chemical reaction site or reactor, as a mechanical or electrical device, as a self-reproducing or information transmitting entity, and so on. In short, the idea that the common size of research objects might be a sufficient ground for the integration of various disciplines is misleading.

2.3 Technological Paradigms Underlying Nanotech Visions

Most reports about the prospects of nanoscale research refer to such values as health, wealth, security, and 'environment'. These are so general that almost everybody would subscribe to them, regardless of their disciplinary professions. Through their appeal to general values or basic human needs, technological visions can provide some integration of different disciplinary perspectives. Yet, once the visionary ways by which such basic values could or should be realized technologically are spelled out, disciplinary distinctions appear. Scholars from different disciplines rely on different 'technological paradigms'. On a very general level, a technological paradigm determines the scope of what is considered technologically feasible and how to approach a technological problem. Technological paradigms usually rest on past successful approaches within the discipline; they are applied to new issues by analogical or metaphorical reasoning rather than by deduction or scientific prediction; and they incorporate metaphysical concepts such as nature or the human-nature relationship.

Current prospects and visions of nanotechnology refer to several different technological paradigms, of which for reasons of brevity I discuss only the two most frequently mentioned: 'atom-by-atom-manipulation' and 'self-assembly' or 'self-organization'.

'*Atom-by-atom-manipulation*' was fostered when scanning probe microscopes (STM, AFM, etc.) turned from mere surface imaging instruments (since about 1981) into surface imaging and 'manipulation' instruments (since 1986), such that individual atoms could be moved and monitored almost simultaneously. Extending the approach to three dimensions, visionaries like E. Drexler conceived atom-by-atom-manipulation as the making of any molecular structure from individual atoms by sticking them together with ultra-atomic precision, once a suitable device – a so-called 'universal assembler'[10] – has been manufactured. The technological paradigm behind this vision of a new way of doing synthetic chemistry is clearly derived from mechanical engineering by extrapolating high-precision manufacturing to the subatomic scale. (Correspondingly, Drexler's vision of 'self-assemblers' repeats the historical step from the manufacturing of machines to that of tool making machines.) Indeed, the most advanced approach in this field, namely micro-lithography, is also called the 'top-down approach' of nanotechnology. 'Atom-by-atom-manipulation' promises nanotechnological success by keeping to mechanical engineering's virtues of high-precision and complete human control over the technological process and also over the matter involved, to the extent that one might worry about the role of chemical bonding in this picture.

'*Self-assembly*', although having a much longer history, became a new mode of both conceptualizing chemical processes and doing synthesis in the 1980s when chemists noticed that, under certain experimental conditions, complex series of reaction steps take place, leading to larger and more complex molecular structures than would be available by classical chemical synthesis. In self-assembly, the intermediary product of the first reaction step triggers or catalyses the second one which in turn favors a third step, and so on, in a rapid series of reactions leading to a complex product. It is the art of the chemists, as they see it, to initiate the series of steps by favorable conditions that direct the entire process toward the desired nanoscale product. Besides conventional conditions, the crucial starter can be a 'template' molecule that functions like a mould or a model for the self-assembly of components. The term 'self-assembly' already reveals that chemists consider a second agency to be at work here that is usually referred to as 'Nature'. And since they find many models of such processes in living beings, they frequently describe the approach of 'chemical synthesis by self-assembly' as based on 'learning from Nature' or 'biomimetic'. This is only one of many instances in which that fundamental notion of alchemy, indeed its basic technological paradigm, is still influential in today's chemistry (Schummer 2003).

The difference between the two technological paradigms could not be greater. 'Atom-by-atom-manipulation' highlights the virtues of high-precision and total human control over the whole material process ('nature'), which would require complete deterministic understanding of all possible events in classical mechanical terms. 'Self-assembly' focuses on virtually selected starting conditions and relies, for the rest, on the virtues of 'Nature'. Although an understanding of 'self-assembly' in terms of chemical thermodynamics and kinetics is important, a complete deterministic understanding is usually regarded beyond reach, and not necessarily required for synthetic success. In fact, many chemists consider 'self-assembly' smarter and superior to the almost two century old approach of classical chemical synthesis, which is a kind of 'atomic-group-by-atomic-group-manipulation' based on the non-mechanical theory of chemical structures and reaction mechanisms.

Since both technological paradigms play a leading role in current nanotechnology, it is hard to see how research approaches guided by such opposing views could ever merge toward interdisciplinary collaboration. The recent Drexler-Smalley debate, their mutual misunderstandings and misconceptions, provides an excellent example of how chemists and mechanical engineers can be talking at cross-purposes, each relying on their own technological paradigm.[11] The debate illustrates that metaphysical notions rooted in history and disciplines pose strong barriers not only to interdisciplinarity and mutual understanding. They can also cause hostility if each party denies the other the expertise due to the 'wrong' technological paradigm.

3. Conclusion

Given the need for interdisciplinarity in nanoscale research, the current situation is not very encouraging. Despite their multi-disciplinary appearance, newly launched 'nano journals' contain hardly more interdisciplinary research than typical mono-disciplinary journals. Obviously, interdisciplinarity is much more difficult to achieve than multidisciplinarity. In this paper, I have pointed out two of the cognitive reasons. First, the widely proclaimed common ground – the nanometer scale of objects – is too weak to integrate different disciplinary perspectives. Second, nanotech visions that are meant to orient researchers towards common goals refer to technological paradigms that are rooted in different disciplines and may, in contrast, pose strong barriers to interdisciplinarity. My conclusion is that the present situation requires serious thinking and rethinking about the cognitive conditions and possibilities of interdisciplinarity in nanoscale research.

My critical conclusion comes at a time when political ambitions, at least in the US, further extend the reach of interdisciplinarity (Roco & Bainbridge 2002, Khushf 2004). Nanotechnology, wrongly considered a homogenous field, is supposed to be one of four fields that combine to form the future scientific landscape, the other three being biotechnology, information science, and cognitive science. The result shall be a super-interdisciplinary structure of the whole of science, including technology, social sciences, and the humanities – a new unity built on the pragmatic goal of improving human performance instead of the dismissed idea of physicalistic 'reductionism'. Although that vision complies with 'anti-disciplinary' and anti-reductionist ideas advanced in recent science studies, the actual situation in current nanoscale research gives rise to serious doubts (see also Schummer 2004). Instead of discussing such Big Pictures, detailed philosophical work is needed to understand both the chances of and the barriers to interdisciplinarity caused by the similarities and differences between the disciplines.

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Notes

[1] For a report that calls for interdisciplinarity even in its title, see Malsch 1997.

[2] Still the best survey with extensive bibliography is Klein Thompson 1990; a more recent bibliography has been prepared by Brandl 1996. Recent monographs and anthologies include Kline 1995, Klein Thompson 1996, Galison & Stump 1996, Umstätter & Wessel 1999, Weingart & Stehr 2000, Käbisch, Maaß & Schmidt 2001, Moran 2002; see also the ongoing online discussion of papers published since April 2003 by Interdisciplines [http://www.interdisciplines.org/interdisciplinarity].

[3] A great many books with 'interdisciplinary' in their titles result from *studium generale* lecture series on some topic with speakers from different disciplines. All of these books that I have seen are really multidisciplinary, that is, a collection of disciplinary essays without any reference to each other.

[4] For nanoscale research the most relevant recent case study is on the discipline formation of materials science since about 1960, see Bensaude-Vincent 2001.

[5] For an excellent account of the manifold 'fallacies of projection' from physics to other discipline, see Kline 1995, particularly part 4.

[6] For a case study on the historiography of psychology, see Geuter 1983.

[7] The results of this section are taken from a much more comprehensive scientometric study of eight nano journals, which also includes details on various methods of measuring interdisciplinarity (Schummer 2004).

[8] NSET, February 2000 (http://www.nsf.gov/home/crssprgm/nano/omb_nifty50.htm).

[9] More exactly, Chemical Abstracts registered 15,459,282 new substances in 2003 of which 13,808,462 were biosequences (CAS 2004, p. 7).

[10] Drexler (1986, chapter 1). Unlike Drexler, Stephenson (1995) uses the term 'matter compiler' which refers to computer science rather than to mechanical engineering.

[11] See *Chemical & Engineering News*, 81 (2003), No. 48, pp. 37-42 [http://pubs.acs.org/cen/coverstory/8148/8148counterpoint.html]

References

Bensaude-Vincent, B.: 2001, 'The Construction of a Discipline: Materials Science in the United States', *Historical Studies in the Physical and Biological Sciences*, **31**, 223-248.

Brandl, M. Th.: 1996, *Interdisziplinarität: Eine ausgewählte Bibliographie zu Interdisziplinarität, Studium generale, Einheit der Wissenschaften und Allgemeinbildung*, Mainz: Universität Mainz.

CAS: 2004, *CAS Statistical Summary 1907-2003*, Columbus, OH: Chemical Abstract Service.

Drexler, K. E.: 1986, *Engines of Creation: The Coming Era of Nanotechnology*, New York *et al.*: Anchor Pr., Doubleday.

Galison, P.; Stump, D. J. (eds.): 1996, *The Disunity of Science. Boundaries, Contexts, and Power*, Stanford: Stanford University Press.

Geuter, U.: 1983, 'The Uses of History for the Shaping of a Field: Observations on German Psychology', in: Graham, L; W. Lepenies & P. Weingart (eds.), *Functions and Uses of Disciplinary Histories* (*Sociology of the Sciences*, vol. 7), Dordrecht: Kluwer, pp. 191-228.

Gibbons, M.; Limoges, C.; Nowotny, H.; Schwartzman, S.; Scott, P.; Trow, M.: 1994, *The New Production of Knowledge: The Dynamics of Science and Research in Contemporary Societies*, London: Sage.

Käbisch, M.; Maaß, H.; Schmidt, S. (eds.): 2001, *Interdisziplinarität: Chancen, Grenzen, Konzepte*, Leipzig: Leipziger Universitätsverlag.

Khushf, G.: 2004, 'A Hierarchical Architecture for Nano-scale Science and Technology: Taking Stock of the Claims About Science Made By Advocates of NBIC Convergence', in: D. Baird, A. Nordmann & J. Schummer (eds.), *Discovering the Nanoscale*, Amsterdam: IOS Press, pp. 21-33 (this volume).

Klein Thompson, J.: 1990, *Interdisciplinarity: History, Theory, and Practice*, Detroit: Wayne State University Press.

Klein Thompson, J.: 1996, *Crossing Boundaries: Knowledge, Disciplinarities, and Interdisciplinarities*, Charlottesville, VA: University Press of Virginia.

Kline, St. J.: 1995, *Conceptual Foundations for Multidisciplinary Thinking*, Stanford, CA: Stanford University Press.

Malsch, I.: 1997, *The Importance of Interdisciplinary Approaches: The Case of Nanotechnology* (*IPTS Report No. 13*, Seville, Spain) [http://www.jrc.es/iptsreport/vol13/ english/Tec1E136.htm].

Moran, J.: 2002, *Interdisciplinarity*, London: Routledge.

Roco, M.C.; Bainbridge, W.S. (eds.): 2002, *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and the Cognitive Science*, Arlington, VA: National Science Foundation.

Schummer, J.: 2003, ‘The Notion of Nature in Chemistry’, *Studies in History and Philosophy of Science*, **34**, 705-736.

Schummer J.: 2004, ‘Multidisciplinarity, Interdisciplinarity, and Patterns of Research Collaboration in Nanoscience and Nanotechnology’, *Scientometrics*, **59**, 425-465.

Schummer J.: 2005, ‘Reading Nano: The Public Interest in Nanotechnology as Reflected in Book Purchase Pattern’, *Public Understanding of Science*, 14, no. 2 (forthcoming).

Stephenson, N.: 1995, *The Diamond Age*, New York: Bantam Books.

Umstätter, W.; Wessel K.-F. (eds.): 1999, *Interdisziplinarität – Herausforderung an die Wissenschaftlerinnen und Wissenschaftler*. *Festschrift zum 60. Geburtstag von Heinrich Parthey*, Bielefeld: Kleine Verlag.

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